Final baseline assessment of the South African sardine resource using data from 1984-2018

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The quantitative assessment of the South African sardine resource, using data from 1984 to 2018 has been finalised. This two mixing-component model assumed no stock recruitment relationship during conditioning. The west component abundance was estimated to be about 12% of the historical (1984-2018) average, with a biomass of 51 thousand tons in November 2018. The south component abundance was estimated to be about 95% of the historical (1984-2018) average, with a biomass of 560 thousand tons in November 2018. Results are only given at the joint posterior mode.

Introduction

An initial assessment of the South African sardine resource, based on data from 1984-2018, was used to provide short term management advice early in 2019 (de Moor 2019a,b). In addition to finalisation of the data, a number of model assumptions have been investigated during the course of 2019 (e.g. de Moor 2019c, de Moor *et al.* 2019a) and recently this year. This document presents results for a finalised baseline assessment using data from 1984-2018, assuming the sardine population consists of two mixing 'components', with a west component distributed west of Cape Agulhas and a south component distributed south-east of Cape Agulhas. The alternative hypothesis of south coast winter spawning is still being investigated and will be reported on separately.

Population Dynamics Model

The population dynamics model for the South African sardine resource is given in Appendix A. All model parameters are defined in Tables A1 and A2. The data used in this assessment were described in de Moor *et al*. (2019b).

The following changes have occurred since the initial 2019 assessment, at which time the annual growth curve had been updated with a cohort growth curve:

i) The data were corrected and updated.

ii) The autocorrelated age at which length is zero (equation A8) was been revised.

iii) The break-points in the length-at-age distribution were aligned to correspond with the length classes in which data were provided.

iv) The growth curve of the western component was revised such that the somatic growth rate parameter (κ_j) was increased for ages $\leq$ 6 months while maintaining both continuity and derivative continuity at $a = 0.5$.

v) There was been a substantial reduction in the range of the prior on these associated residuals (η_y^t).

vi) A time-invariant survey weight-at-length was used (see footnotes associated with equations A11 and A13).

vii) The commercial selectivity-at-length relationship was changed to be year- and quarter-specific on the west component (Figure 7), improving the fit of the commercial length frequency data.

viii) Sardine weight-at-length was changed to be stock-dependent (OLSPS 2020).

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Results and Discussion

The model was able to fit the survey estimates of abundance well in most years (Figures 1 and 2). The years for which the model predicted value exceeded the 95% confidence interval of the survey estimate typically corresponded to years for which there was conflicting information between the November biomass and May/June recruit surveys. The model estimated survey biomass in November 2018 was 39 000t west of Cape Agulhas and 431 000t east of Cape Agulhas, compared to the survey estimates of 35 000t and 56 000t, respectively. The high estimate of south coast biomass in November 2018 – compared to the survey estimate – was influenced by the November length frequency (with few large fish) given the absence of a May/June survey estimate of recruitment in 2018, as well as the commercial length frequency and parasite prevalence data. The model estimated survey bias indicates that the survey estimates about 77% of true biomass. The west component abundance was estimated to be about 12% of the historical (1984-2018) average, with a biomass of 51 000t in November 2018. The south component abundance was estimated to be about 95% of the historical (1984-2018) average, with a biomass of 560 000t in November 2018.

High proportions of west component fish were still estimated to move to the south component in some recent years, however the primary movement in terms of biomass occurred during the pulse years at the turn of the century (Figure 3).

The model fit to the survey length frequencies was relatively good (Figures 5, 6, Appendix B). The model estimated a higher survey selectivity for small lengths for the south component compared to the west component (Figure 4), likely given the higher proportions observed at small lengths on the south component compared to the west component (Figure 6). These higher proportions of small fish on the south coast in November have been hypothesised to result from winter spawning on the south coast. This is presently being investigated through a separate hypothesis.

Allowing commercial selectivity-at-length to vary by year (Figure 7) has resulted in an improved fit to the commercial length frequency data (Table 1, Figures 8 and 9).

Figure 10 shows the growth curves which were modelled to vary by cohort. The average $t_{0,j,y}$ from the von Bertalanffy growth curve for the south component was 0.08 (close to November) with a maximum difference in $t_{0,j,y}$ between cohorts of approximately 8 months. This appears reasonable. However, even with an adjustment to the growth curve for the west component, the average $t_{0,j,y}$ was approximately 6 months before November, with a maximum difference in $t_{0,j,y}$ between cohorts of about 6 months. A greater adjustment to the growth curve to bring this average closer to November resulted in a substantially poorer fit to some of the length frequency and parasite prevalence data. Figure 11 shows the length-at-age distributions for one example year.

The model estimated some years of high sardine infection by the "tetracotyle" type digenean endoparasite and other years of low infection. This is not unexpected given indications that sardine are infected when parasites are released in sporadic bursts. The model fit to the parasite prevalence data is given in Figure 13.

The model estimated November recruitment is plotted against effective spawning biomass in Figure 14, indicating the low west component spawner biomass and recruitment in recent years.

Figure 15 shows the historical harvest proportion on the sardine, which has often been substantially higher on the west component than on the south component since the end of the early-2000s pulse.

Further Work

Readers are reminded that although only point estimates have been presented herein, there is error in these values. Posterior distributions have not yet been estimated given time constraints.

During the course of this work, additional sensitivity tests have been added to the 'typical' list considered and should be considered with future assessments. The full list of sardine sensitivity tests now includes:

- alternative time-invariant natural mortality
- alternative natural mortality with changes during and/or after pulse years
- density dependent natural mortality to account for the possibility of higher M when the prey population decreases by the predator populations remain relatively unchanged
- alternative maturity-at-length relationships over time and between components
- alternative stock-recruitment relationships (estimated during and/or after conditioning)
- alternative date of west-to-south movement (1 August or 1 August and 1 November)
- standard deviation associated with the survey proportion-at-length data is estimated annually (through closed form solution and bounded between [0.04,0.1]) and not as a time-invariant standard deviation
- standard deviation associated with the commercial proportion-at-length data is estimated annually (through closed form solution and bounded between [0.04,0.1]) and not as a time-invariant standard deviation
- alternative prevalence data including samples from 20-22°E
- fix the bias in the November survey at 0.5 and 1.5
- estimate additional variance in the November survey
- estimate additional variance in the recruit survey
- down weight survey and commercial proportion-at-length data ($0.3w_{propl}^{sur}$ and $0.3w_{propl}^{com}$)

Acknowledgements

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Table 1. The contributions to the posterior distribution for this final baseline assessment compared to the initial 2019 sardine assessment (de Moor 2019a). The middle row shows the contributions to the posterior distribution from the model of de Moor (2019a) fit to the revised data.

	-ln(Likelihood)	-ln(Posterior)	-ln(Likelihood) Nov	Rec	Com Prop-at-length	Survey Prop-at-length	Prev-at-length	-ln(Prior) k_{ac}^{S}	$move_{1,y}$	η_y^t	$\bar{l}_{1,y}$	Penalty
Initial assess-ment	909.9	923.8	56.6	38.4	-429.6	-383.6	1628.1	-1.4	-30.7	45.9	-	0.1
Rev data	917.4	930.9	56.3	38.5	-419.4	-385.0	1627.1	-1.4	-30.7	45.52	-	0.1
Final assess-ment	913.7	981.9	60.3	39.6	-432.7	-382.8	1629.2	-1.3	-30.3	-15.0	114.5	0.3

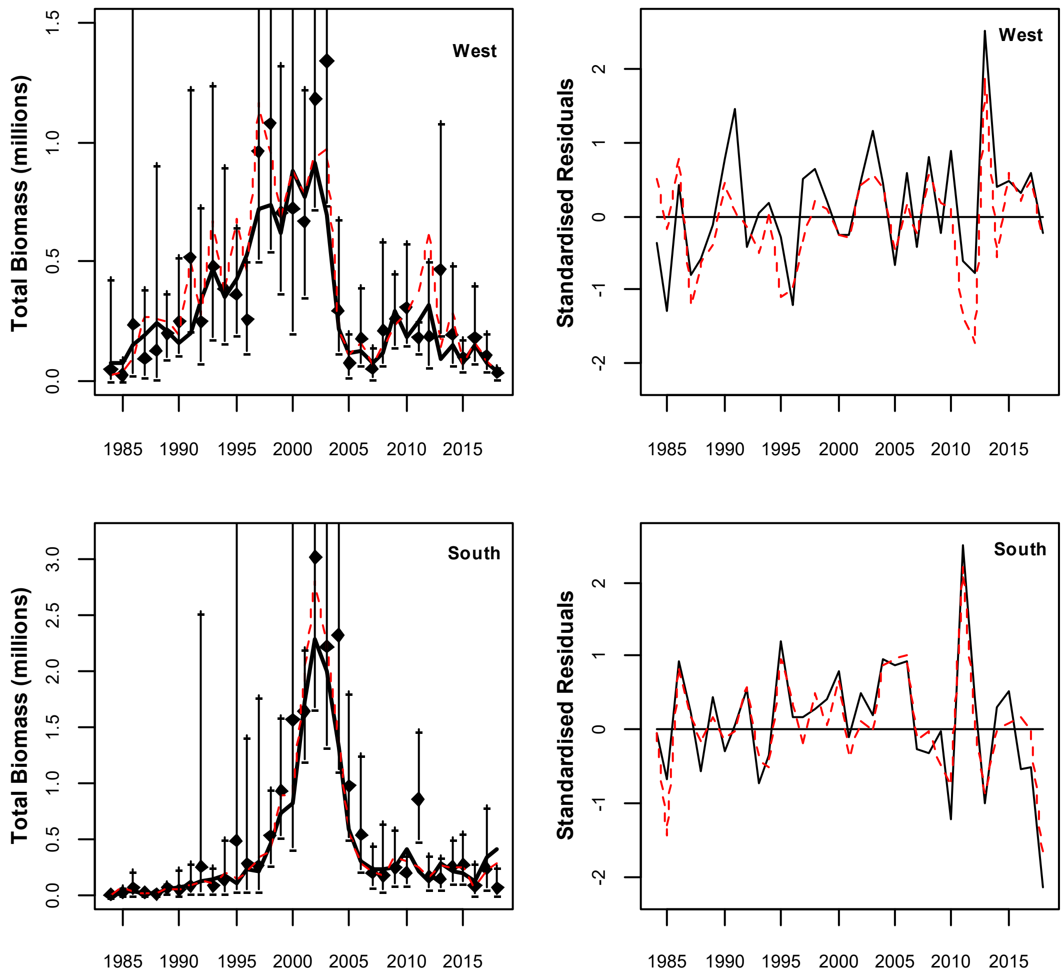

Figure 1. Acoustic survey estimated and model predicted November sardine total biomass from 1984 to 2018. The observed indices are shown with 95% confidence intervals. The standardised residuals (i.e. the residual divided by the corresponding standard deviation, including additional variance where appropriate) from the fits are given in the right hand plots. The red line indicates the November biomass and residuals predicted by de Moor (2019a) with slightly different data in 1995.

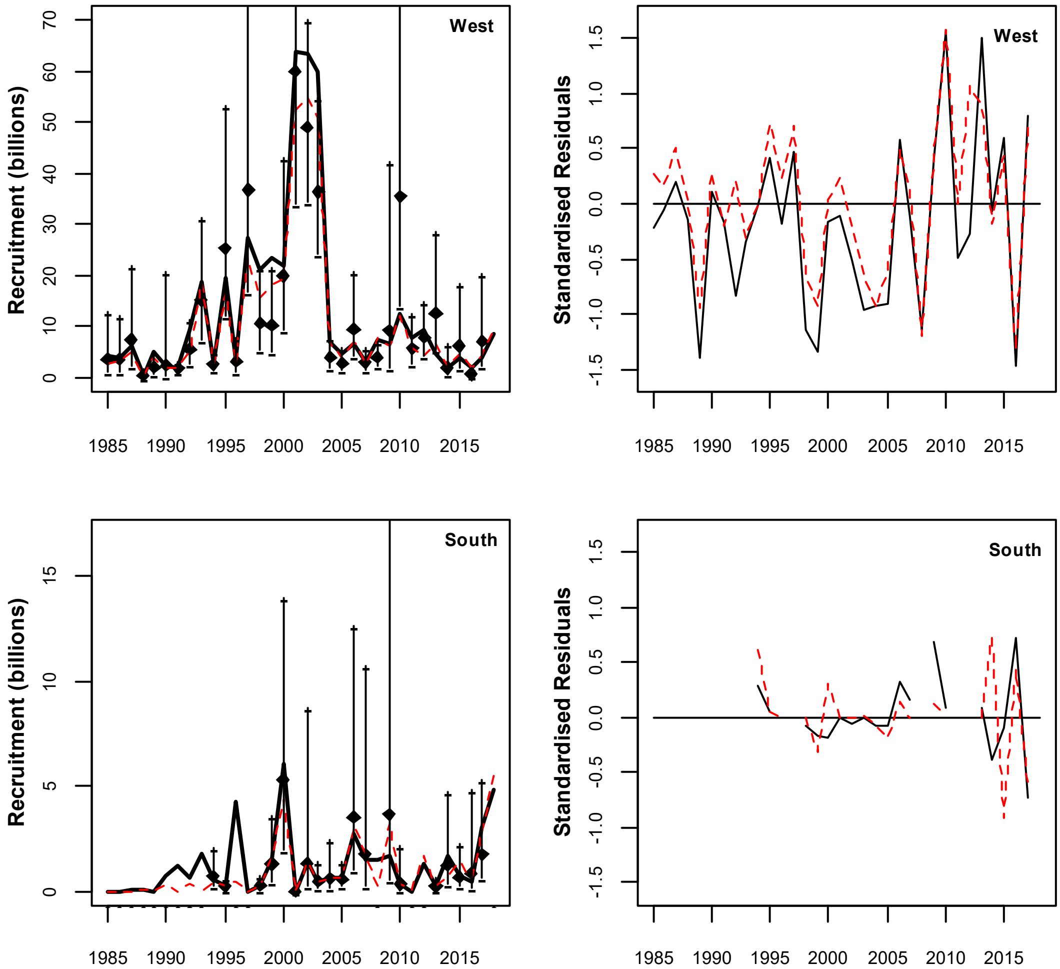

Figure 2. Acoustic survey estimated and model predicted sardine recruitment numbers from May/June 1985 to 2018. There was no survey observation in 2018; the model predicted value corresponds to the recruitment predicted at 8th June 2018 which is the average start date of the survey from 2016, 2017 and 2019 surveys. The survey indices are shown with 95% confidence intervals. The standardised residuals from the fit are given in the right hand plots. The red line indicates the May recruitment and residuals predicted by de Moor (2019a) with different data in some years.

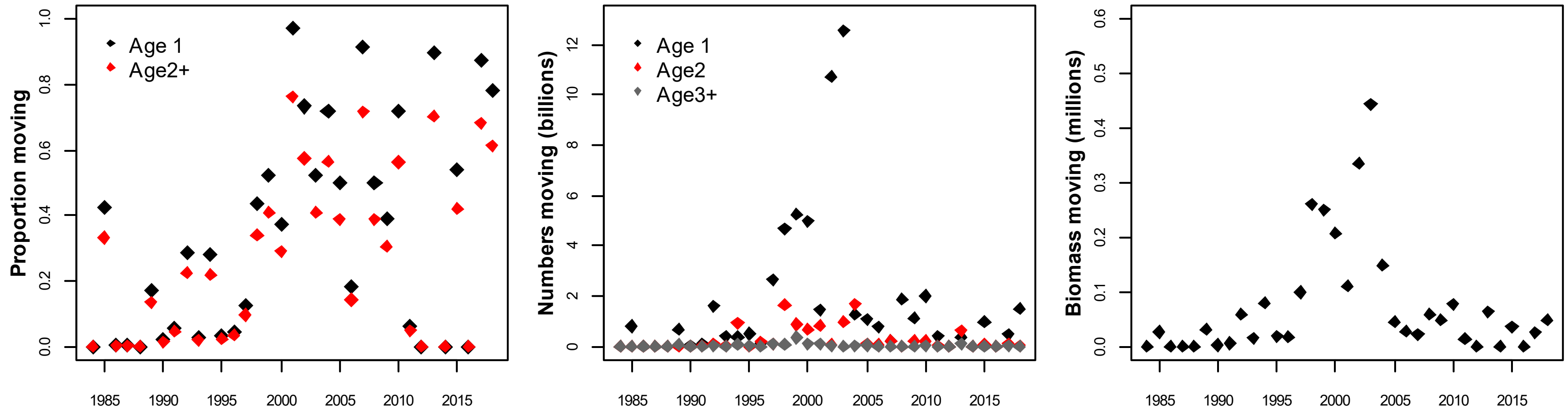

Figure 3. Model estimated proportion of 1-year-olds and 2+-year-olds which move from the "west" component to the "south" component in November. The middle plot shows the numbers of 1-, 2- and 3-year olds moving while the right hand plot shows rough[1] estimates of the annual biomass moving from the west to south component.

[1] Calculated using the average of west and south component weights-at-age.

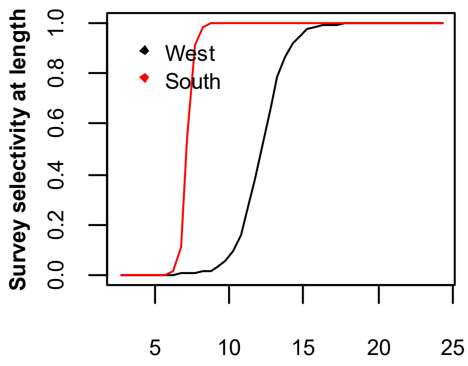

Figure 4. The model estimated November survey selectivity at length.

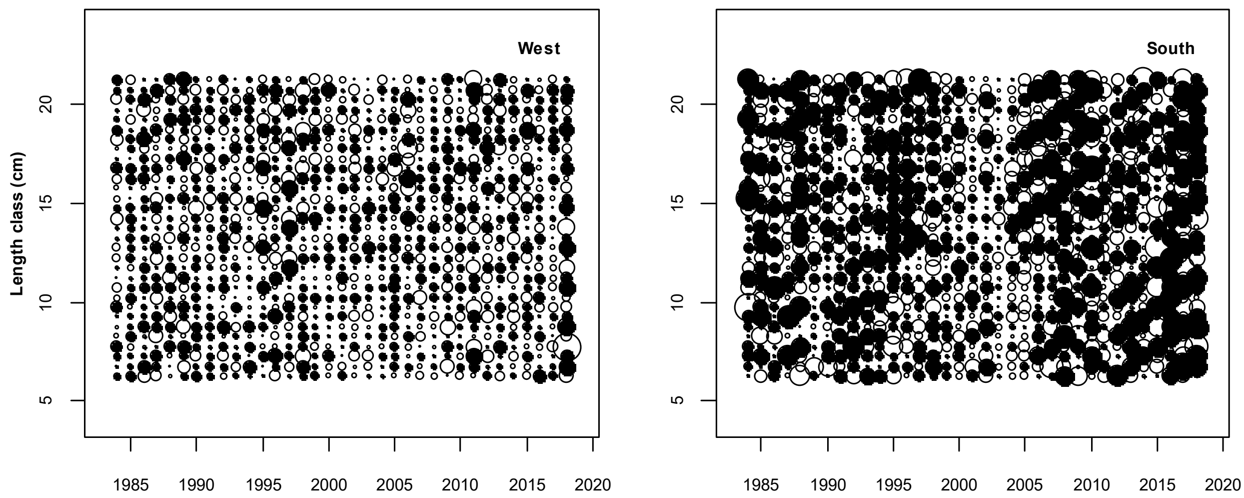

Figure 5. Residuals from the fit of the model predicted proportions-at-length in the November survey to the hydroacoustic survey estimated proportions.

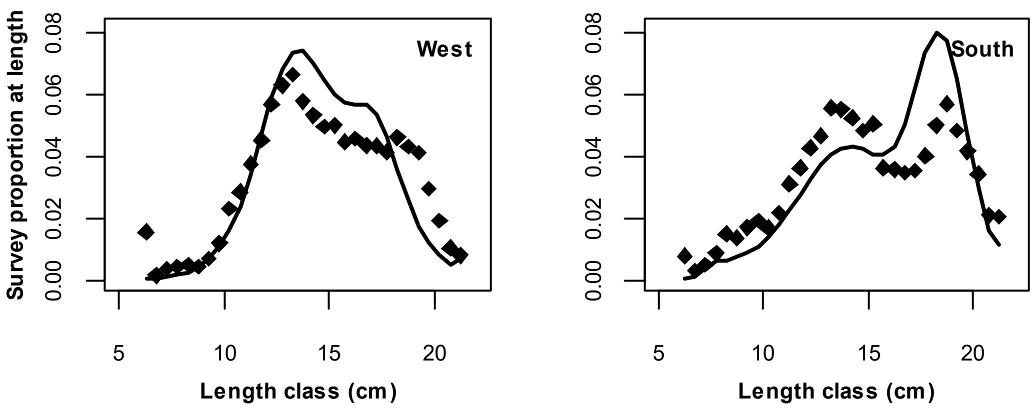

Figure 6. Average (over all years) model predicted and observed proportion-at-length in the November survey.

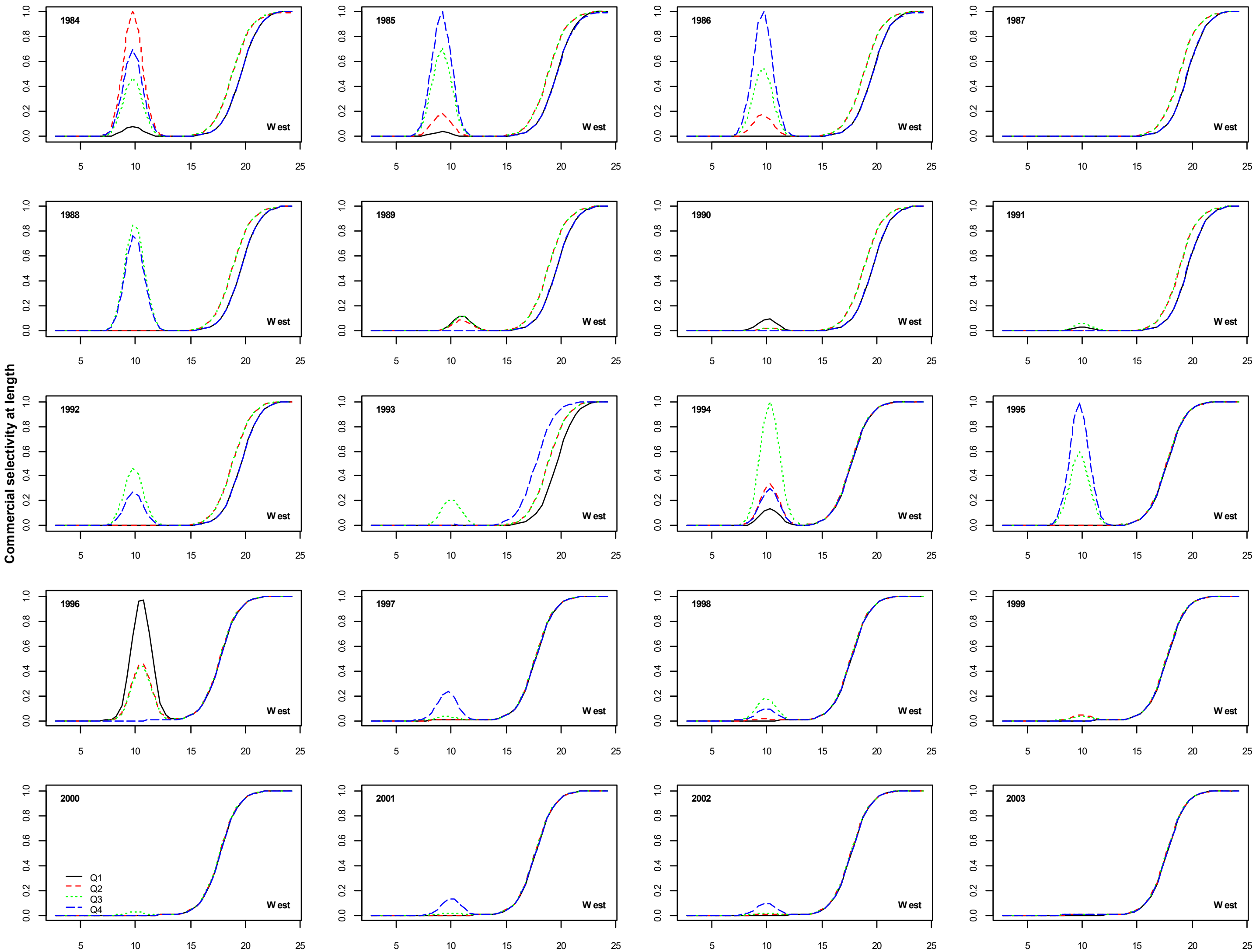

Figure 7. The model estimated commercial selectivity at length.

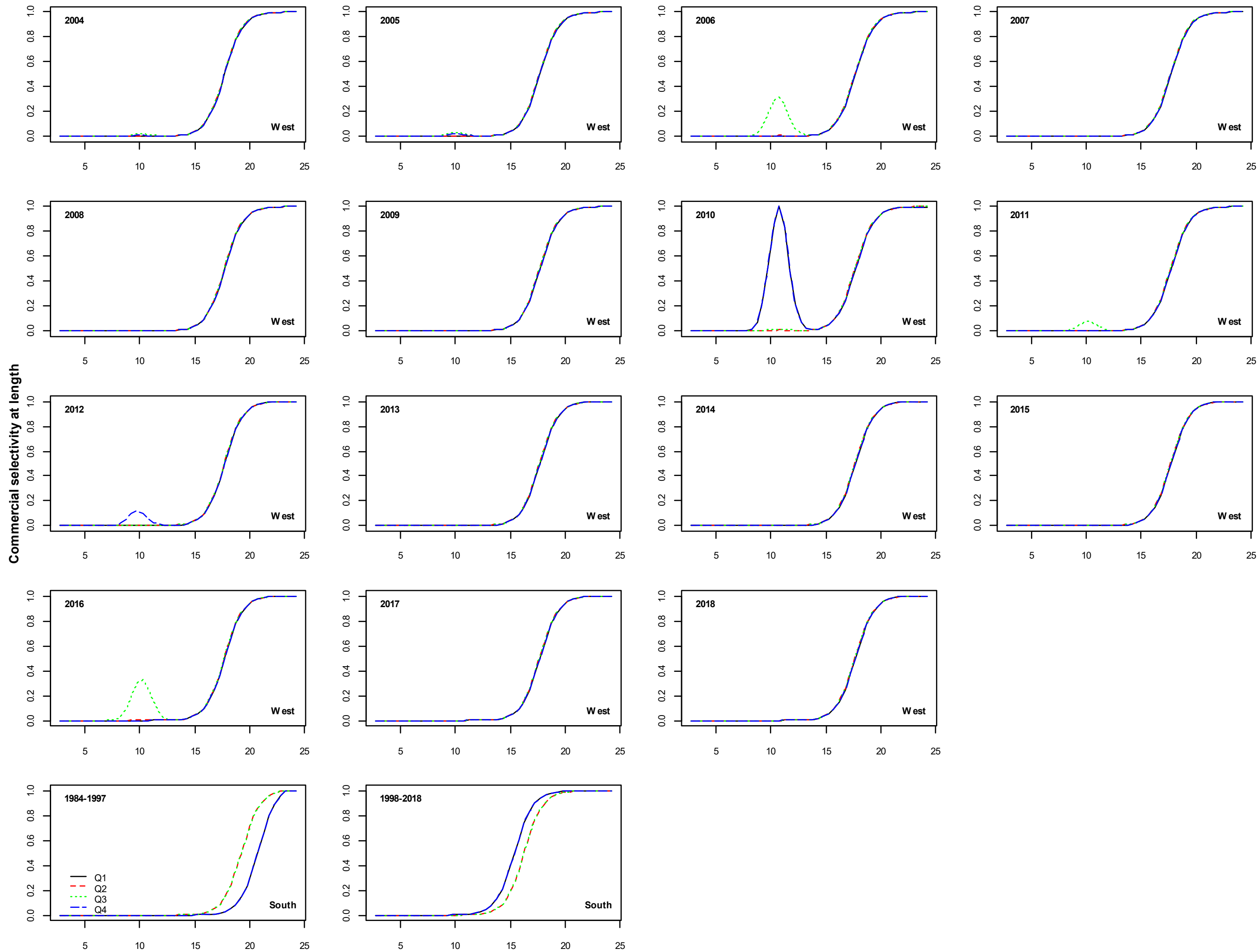

Figure 7 (continued).

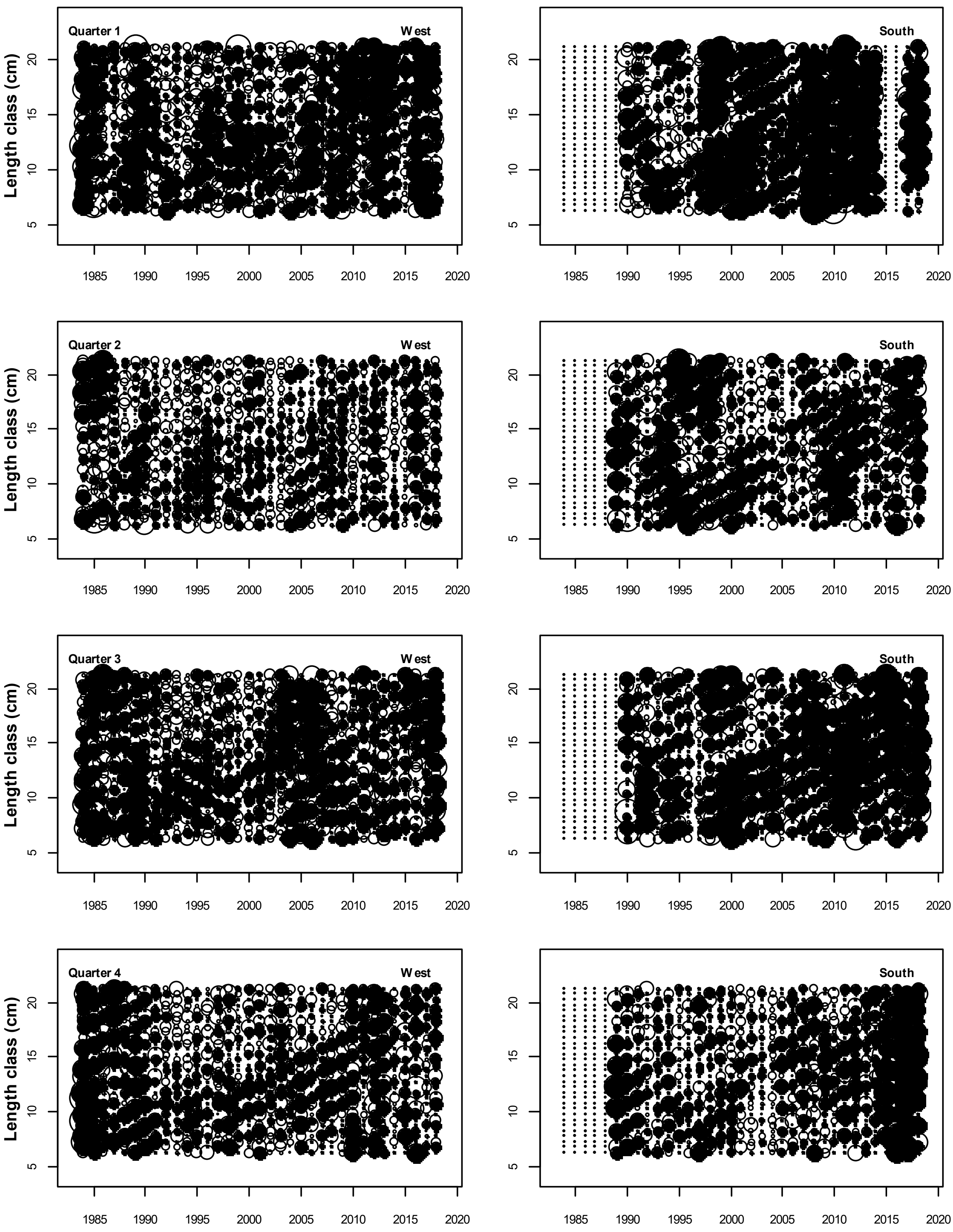

Figure 8. Residuals from the fit of the model predicted proportions-at-length in the quarterly commercial catch to the observed proportions.

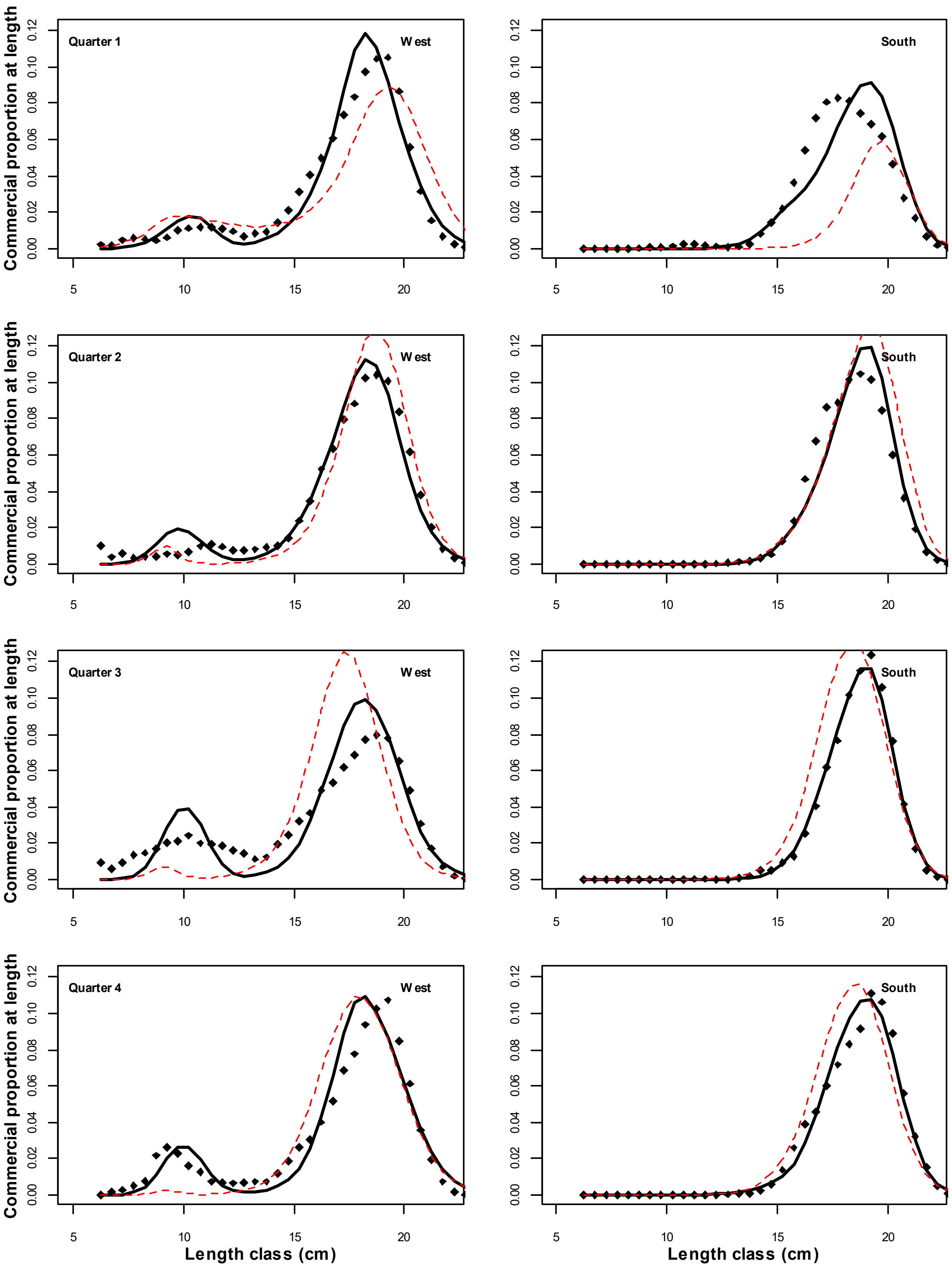

Figure 9. Average (over all quarters and years) model predicted and observed proportion-at-length in the commercial catch (top row), and average (over all years) quarterly model predicted and observed proportions-at-length in the commercial catch (subsequent rows). See Appendix B for plots for each year and quarter. The red line indicates the average model predicted by de Moor (2019a) fit to the same data as this assessment.

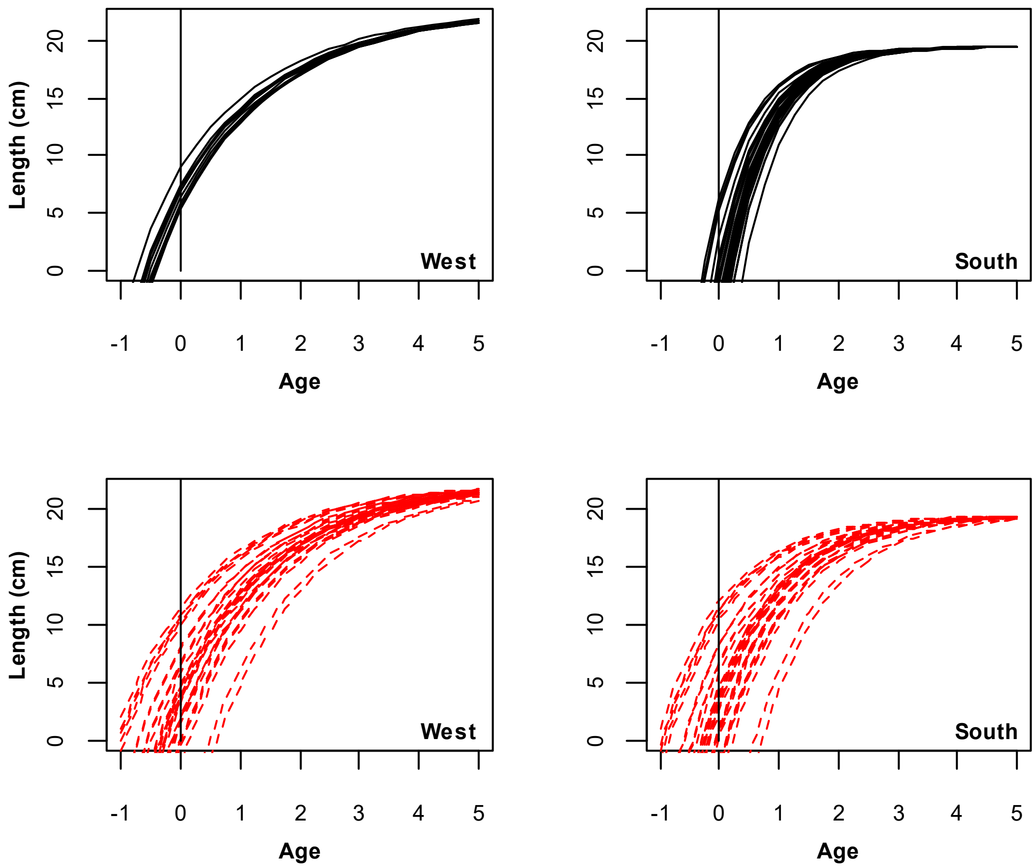

Figure 10. The von Bertalanffy growth curves (by cohort) estimated by allowing for auto-correlated residuals for the variation about the age at which length is zero. The lower plots shows the von Bertalanffy growth curves (by cohort) estimated by de Moor (2019a) in red.

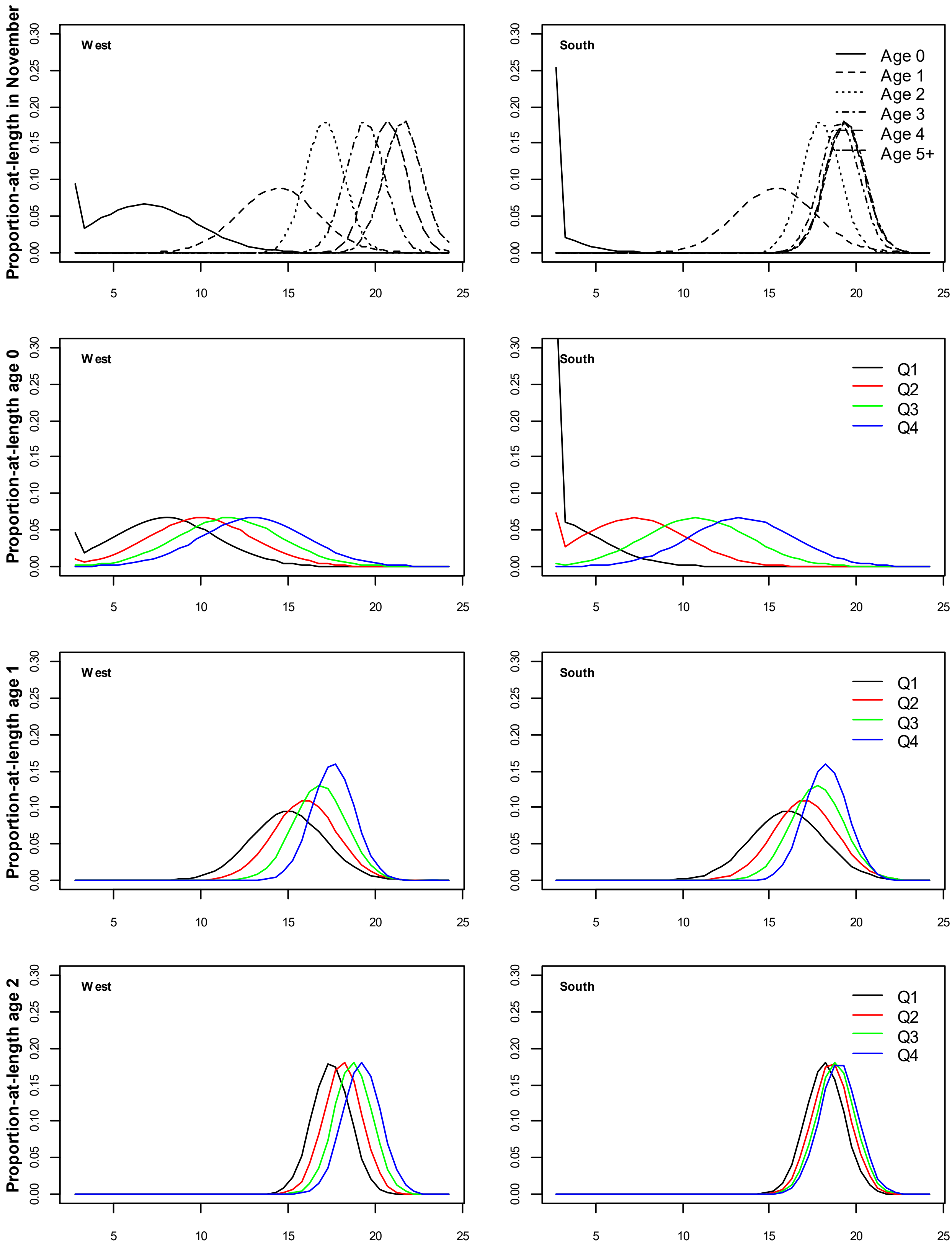

Figure 11. The model estimated distributions of proportions-at-length for each age **in 2010**, given at the time of the biomass survey (1 November, top row), and middle of each quarter of the year (corresponding to the times commercial catch is modelled to be taken) for age 0, 1 and 2 (subsequent rows).

Figure 12. The model estimated proportion of west component sardine infected with the parasite between 2008 and 2018. (Annual infection rate is arbitrarily assumed to be 0 prior to 2008.)

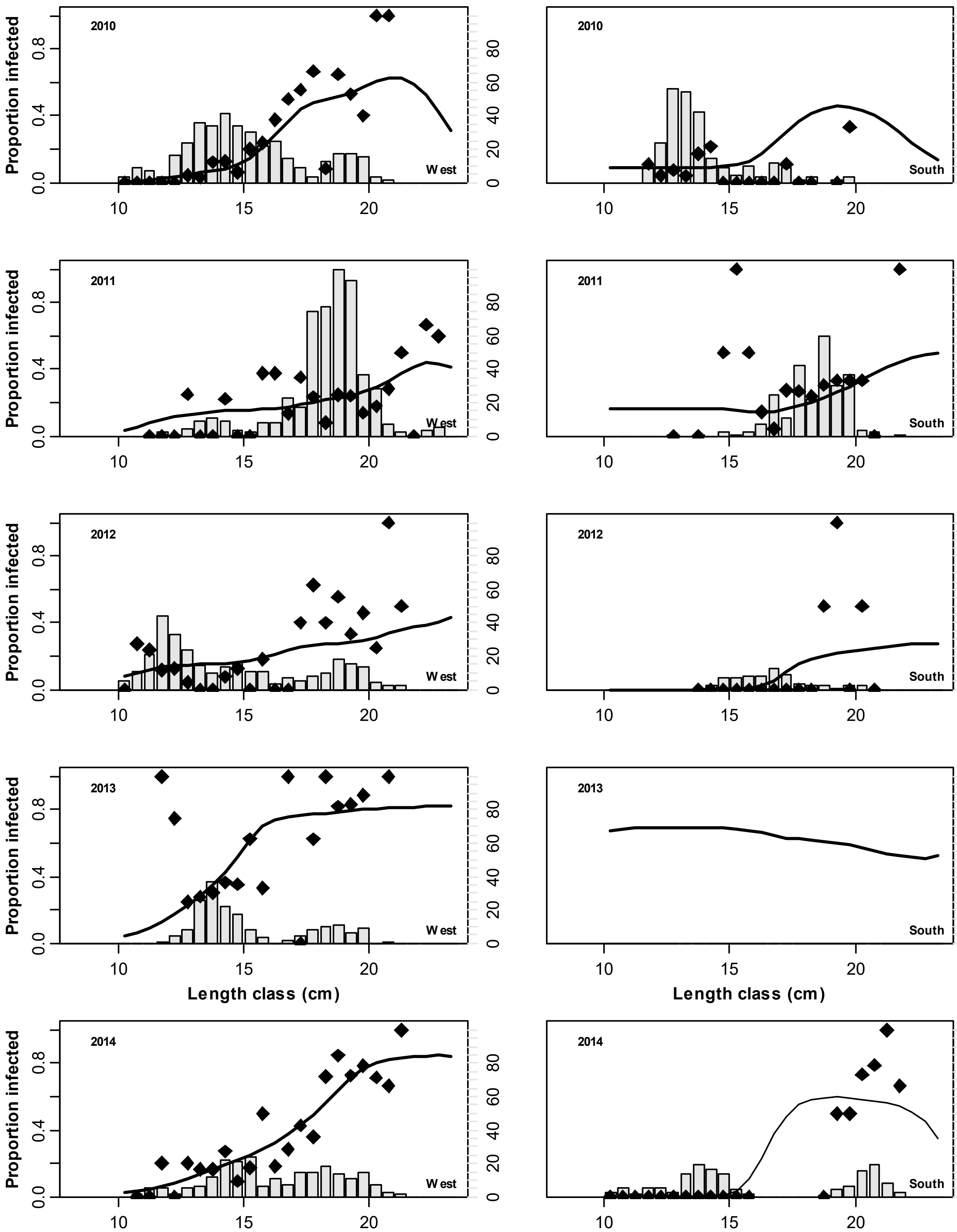

Figure 13. The model estimated proportions-at-length of west and south stock sardine infected with the parasite (i.e. parasite prevalence-by-length) between 2010 and 2018 together with the observed proportions-at-length. The sample size for each length class is given by the grey bars, plotted against the right vertical axis.

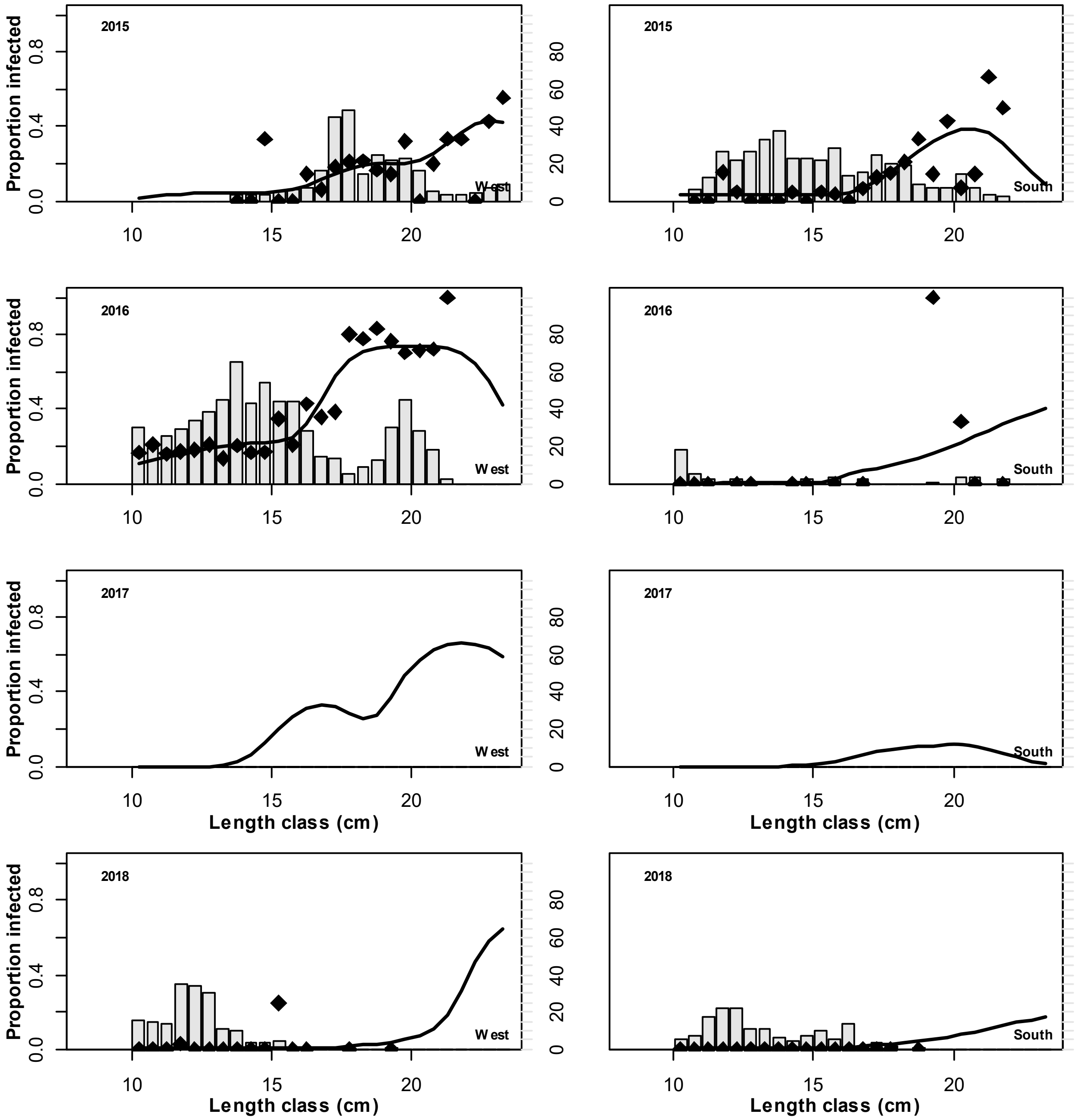

Figure 13 (continued).

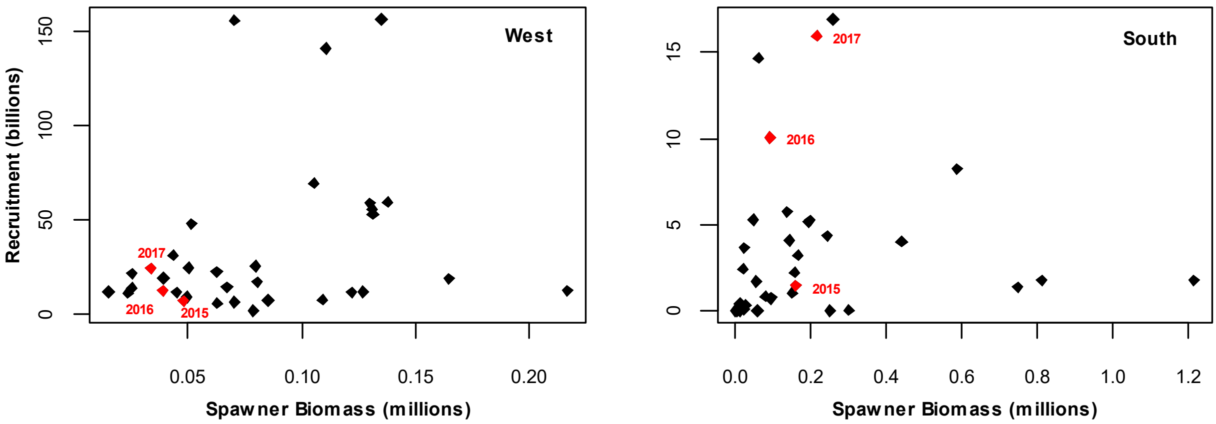

Figure 14. Model predicted sardine recruitment (in November) plotted against spawner biomass from November 1984 to November 2017.

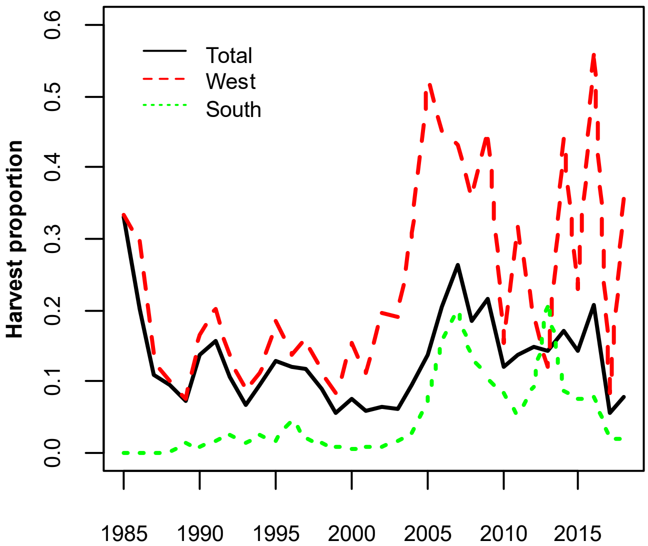

Figure 15. The exploitation rate (simply calculated as the observed annual (Nov-Oct) catch tonnage as a proportion of the model predicted total biomass).

Appendix A: Bayesian assessment model for the South African sardine resource

This assessment provides the generalised operating model for the South African sardine resource (used for this baseline two mixing-component hypothesis as well as a single stock hypothesis[2]). The assessment is run from November $y_1 = 1984$ to November $y_n = 2018$, with the following subscript notation:

- quarters $q = 1$ denoting November $y-1$ to January y, $q = 2$ denoting February to April y, $q = 3$ denoting May to July y and $q = 4$ denoting August to October y;
- ages $a = 0$ to a plus group of $a = 5^+$;
- lengths from a minus group of $l = 2.5^- cm$ to a plus group of $l = 24^+ cm$;
- components $j = W$ or $j = S$ denote the west and south components, respectively, where only the west component equations are used in the single component hypothesis;
- infection $p = NI$ or $p = I$ denote the sardine uninfected and infected with the digenean 'tetracotyle-type' metacercarian endoparasite, respectively.

All parameters are defined in Tables A1 and A2.

Population Dynamics

Numbers-at-age at 1 November before movement or infection

$$N^{S*}_{j,p,y,a} = \left(\left(\left(\left(N^S_{j,p,y-1,a-1} e^{-M^S_{y,a-1}/8} - C^S_{j,p,y,1,a-1}\right) e^{-M^S_{y,a-1}/4} - C^S_{j,p,y,2,a-1}\right) e^{-M^S_{y,a-1}/4} - C^S_{j,p,y,3,a-1}\right) e^{-M^S_{y,a-1}/4} - C^S_{j,p,y,4,a-1}\right) e^{-M^S_{y,a-1}/8}$$

$$p = I, NI, y_1 \le y \le y_n, 1 \le a \le 4$$

$$N^{S*}_{j,p,y,5^+} = \left(\left(\left(\left(N^S_{j,p,y-1,4} e^{-M^S_{y,4}/8} - C^S_{j,p,y,1,4}\right) e^{-M^S_{y,4}/4} - C^S_{j,p,y,2,4}\right) e^{-M^S_{y,4}/4} - C^S_{j,p,y,3,4}\right) e^{-M^S_{y,4}/4} - C^S_{j,p,y,4,4}\right) e^{-M^S_{y,4}/8} +$$

$$\left(\left(\left(\left(N^S_{j,p,y-1,5^+} e^{-M^S_{y,5^+}/8} - C^S_{j,p,y,1,5^+}\right) e^{-M^S_{y,5^+}/4} - C^S_{j,p,y,2,5^+}\right) e^{-M^S_{y,5^+}/4} - C^S_{j,p,y,3,5^+}\right) e^{-M^S_{y,5^+}/4} - C^S_{j,p,y,4,5^+}\right) e^{-M^S_{y,5^+}/8}$$

$$p = I, NI, y_1 \le y \le y_n \qquad \text{(A1)}$$

Infection of west component sardine in the two mixing-component hypothesis; in the single component hypothesis $I_y = 0$ as the parasite data have no influence so that they are not included in the likelihood

$$\mathrm{N^{S**}_{W,NI,y,a}} = \left(1 - \mathrm{I_y}\right)\mathrm{N^{S*}_{W,NI,y,a}} \qquad y_1 \le y \le y_n, 1 \le a \le 5^+$$

$$\mathrm{N^{S**}_{W,I,y,a}} = \mathrm{N^{S*}_{W,I,y,a}} + \mathrm{I_y N^{S*}_{W,NI,y,a}} \qquad y_1 \le y \le y_n, 1 \le a \le 5^+$$

$$\mathrm{N^{S**}_{S,p,y,a}} = \mathrm{N^{S*}_{S,p,y,a}} \qquad p = I, NI, y_1 \le y \le y_n, 1 \le a \le 5^+ \qquad \text{(A2)}$$

Movement of west component ($j = W$) sardine to the south component ($j = S$) in the two mixing-component hypothesis; in the single component hypothesis $move_{y,a} = 0$

$$\mathrm{N^{S}_{W,p,y,a}} = \left(1 - \mathrm{move_{y,a}}\right)\mathrm{N^{S**}_{W,p,y,a}} \qquad p = I, NI, y_1 \le y \le y_n, 1 \le a \le 5^+$$

$$\mathrm{N^{S}_{S,p,y,a}} = \mathrm{N^{S**}_{S,p,y,a}} + \mathrm{move_{y,a} N^{S**}_{W,p,y,a}} \qquad p = I, NI, y_1 \le y \le y_n, 1 \le a \le 5^+ \qquad \text{(A3)}$$

[2] For the single stock hypothesis, both abundance indices and proportion-at-length data are combined for the full area and parasite prevalence-by-length is excluded from the likelihood.

Numbers-at-age mid-way through each quarter (for use in catch equations)

$N^S_{j,p,y,1,a} = N^S_{j,p,y-1,a} e^{-M^S_{y,a}/8}$ $\qquad p = I, NI, y_1 \le y \le y_n, 0 \le a \le 5^+$

$N^S_{j,p,y,q,a} = \left(N^S_{j,p,y,q-1,a} - C^S_{j,p,y,q-1}\right) e^{-M^S_{y,a}/4}$ $\qquad p = I, NI, y_1 \le y \le y_n, 2 \le q \le 4, 0 \le a \le 5^+$ (A4)

Numbers-at-length at 1 November (after infection and movement)

The model estimated numbers-at-length range from a 2.5cm minus group to a 24cm plus group, denoted 2.5⁻ and 24⁺, respectively, in the remaining text.

$N^S_{j,p,y,l} = \sum_{a=0}^{5^+} A^{sur}_{j,y,a,l} N^S_{j,p,y,a}$ $\qquad p = I, NI, y_1 \le y \le y_n, 2.5^- cm \le l \le 24^+ cm$ (A5)

The model predicted numbers-at-length of ages 1+ only are given by:

$N^{S,1+}_{j,p,y,l} = \sum_{a=1}^{5^+} A^{sur}_{j,y,a,l} N^S_{j,p,y,a}$ $\qquad p = I, NI, y_1 \le y \le y_n, 2.5^- cm \le l \le 24^+ cm$ (A6)

The proportion of sardine of age a in component j that fall in length group l at 1 November, $A^{sur}_{j,y,a,l}$, is calculated under the assumption that length-at-age is normally distributed about a von Bertalanffy growth curve, with a modification to the somatic growth rate at low ages:

$A^{sur}_{j,y,a,l} \sim N\left(L_{j,y,a}, \vartheta^2_a\right)$ [3]

where $L_{j=1,y,a} = \begin{cases} L^{small}_{j,y-a,\infty}\left(1 - e^{-1.5\kappa_j\left(a - t^{small}_{0,j,y-a}\right)}\right) & a \le 0.5 \\ L_{j,\infty}\left(1 - e^{-\kappa_j\left(a - t_{0,j,y-a}\right)}\right) & a \ge 0.5 \end{cases}$

and $L_{j=2,y,a} = L_{j,\infty}\left(1 - e^{-\kappa_j\left(a - t_{0,j,y-a}\right)}\right)$ $\qquad y_1 \le y \le y_n, 0 \le a \le 5^+, 2.5^- cm \le l \le 24^+ cm$ (A7)[4]

with $t_{0,j,y} = t_{0,j} + \varepsilon^t_y$ [5] (A8)

And $\varepsilon^t_y = \begin{cases} \eta^t_y & y = y_1 \\ \rho^t \varepsilon^t_{y-1} + \sqrt{1 - (\rho^t)^2}\,\eta^t_y & y_1 < y \le y_n \end{cases}$

Natural mortality

Natural mortality is modelled to vary annually in an autocorrelated manner around a median as follows (although the baseline assumes no such correlation – see Table A.1):

$M^S_{y,a=0} = \bar{M}^S_{ju} e^{\varepsilon^{ju}_y}$ with $\varepsilon^{ju}_{1984} = \eta^{ju}_{1984}$ and $\varepsilon^{ju}_y = \rho\varepsilon^{ju}_{y-1} + \sqrt{1-\rho^2}\,\eta^{ju}_y$, $y_1 \le y \le y_n$ (A9)

$M^S_{y,a=1+} = \bar{M}^S_{ad} e^{\varepsilon^{ad}_y}$ with $\varepsilon^{ad}_{1984} = \eta^{ad}_{1984}$ and $\varepsilon^{ad}_y = \rho\varepsilon^{ad}_{y-1} + \sqrt{1-\rho^2}\,\eta^{ad}_y$, $y_1 \le y \le y_n$ (A10)

Spawning biomass and biomass associated with the November survey

$SSB^S_{j,y} = \sum_p \sum_{l=2.5^-}^{24^+} f^S_{j,y,l} N^{S,1+}_{j,p,y,l} w^S_{j,l}$ $\qquad y_1 \le y \le y_n$ (A11)

$SSB^{eff,S}_{j=W,y} = \xi_W SSB^S_{W,y} + (1 - \xi_S) SSB^S_{S,y}$ $\qquad y_1 \le y \le y_n$

$SSB^{eff,S}_{j=S,y} = (1 - \xi_W) SSB^S_{W,y} + \xi_S SSB^S_{S,y}$ $\qquad y_1 \le y \le y_n$ (A12)

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[3] Given the allowance for early/late recruitment in varying $t_{0,y}$ estimates annually, there may be some proportion of this distribution below a length of zero (due to late recruitment). In these cases, this proportion is removed from the proportion-at-length of the minus length class.

[4] The proportion is calculated as the area under the curve between the lower limit and upper limit of length class l. The lower and upper tails are included in the proportions calculated for the minus and plus groups, respectively.

[5] Additive error allows for early or late recruitment. While the timing of recruitment may vary between stocks due to differing environmental conditions on the west and south coasts, the same autocorrelation parameters are assumed here for simplicity reasons.

$$B_{j,y}^S = k_{j,N}^S \sum_p \sum_{l=2.5^-}^{24^+} N_{j,p,y,l}^S w_{j,l}^S \quad ^{67} \qquad y_1 \le y \le y_n \qquad \text{(A13)}$$

Commercial selectivity

$$S_{j,y,q,l} = \begin{cases} 0 & l \le 5.5cm \\ \chi_{j,y,q} exp\left\{-\dfrac{\left(l + 0.25 - \bar{l}_{1,y}\right)^2}{(\sigma_1^{sel})^2}\right\} + \dfrac{1}{1 + exp\{-\left(l + 0.25 - \bar{l}_{2,j,y,q}\right)/(\sigma_2^{sel})^2\}} & 6cm \le l \le l_{max} = 23cm\ ^{8} \\ S_{j,y,q,lmax} & l > l_{max} \end{cases}$$

$$y_1 \le y \le y_n, 1 \le q \le 4 \qquad \text{(A14)}$$

$$S_{j,y,q,a} = \sum_{l=2.5^-}^{24^+} A_{j,y,q,a,l}^{com} S_{j,y,q,l} \qquad y_1 \le y \le y_n, 1 \le q \le 4, 0 \le a \le 5^+ \qquad \text{(A15)}$$

$$A_{j,y,q,a,l}^{com} \sim N\left(L_{j,y,q,a}^{com}, \left[\left(1 - \frac{(2q-1)}{8}\right)\vartheta_a + \frac{(2q-1)}{8}\vartheta_{a+1}\right]^2\right)$$

where $L_{j=1,y,q,a}^{com} = \begin{cases} L_{j,y-a,\infty}^{small}\left(1 - e^{-1.5\kappa_j\left(a+(2q-1)/8-t_{0,j,y-a}^{small}\right)}\right) & a \le 0.5 \\ L_{j,\infty}\left(1 - e^{-\kappa_j\left(a+(2q-1)/8-t_{0,j,y-a}\right)}\right) & a \ge 0.5 \end{cases}$

and $L_{j=2,y,q,a}^{com} = L_{j,\infty}\left(1 - e^{-\kappa_j\left(a+(2q-1)/8-t_{0,j,y-a}\right)}\right)$

$$y_1 \le y \le y_n, 1 \le q \le 4, 0 \le a \le 5^+, 2.5^-cm \le l \le 24^+cm \quad \text{(A16)}\ ^{9}$$

Bycatch in the anchovy directed fishery

$$C_{j,p,y,q,a}^{bycatch} = \begin{cases} N_{j,p,y,q,a}^S F_{j,y,q,a}^{By} & 0 \le a \le 1 \\ 0 & 2 \le a \le 5^+ \end{cases} \ ^{10} \qquad p = I, NI, y_1 \le y \le y_n, 1 \le q \le 4 \qquad \text{(A17)}$$

Catch in the directed sardine and round herring bycatch fisheries

$$C_{j,p,y,q,a}^{dir} = \left(N_{j,p,y,q,a}^S - C_{j,p,y,q,a}^{bycatch}\right) S_{j,y,q,a} F_{j,y,q} \qquad p = I, NI, y_1 \le y \le y_n, 1 \le q \le 4, 0 \le a \le 5^+ \text{(A18)}$$

Total catch

$$C_{j,p,y,q,a}^S = C_{j,p,y,q,a}^{bycatch} + C_{j,p,y,q,a}^{dir} \qquad p = I, NI, y_1 \le y \le y_n, 1 \le q \le 4, 0 \le a \le 5^+ \text{(A19)}$$

Fished proportion of the available biomass from the sardine bycatch with the anchovy directed fishery

$$F_{j,y,q=1,a=0}^{By} = \frac{\sum_{m=11}^{12} \sum_{l<lcut_{y-1,m}} C_{j,y-1,m,l}^{RLF,fleet=3} + \sum_{l<lcut_{y,m}} C_{j,y,1,l}^{RLF,fleet=3}}{\sum_p N_{j,p,y,q=1,a=0}^S}$$

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[6] The biomass in $y_n = 2018$ excludes age 0 fish, although the contribution of age 0 fish to the total biomass should be minor.

[7] A time invariant weight-at-length is used in this equation. Previous assessments adjusted the November weight-at-length annually, informed by the average weight of sardine sampled during the survey, to account for the differing condition factor of sardine at the time of the survey. However, recent discussions have clarified that the hydro-acoustic survey estimate of total biomass depends on the size of the fish swim bladder which depends (through the time invariant target strength relationship) on fish length only but not on the condition (skinniness/fattiness) of the fish at the time of the survey. A time-invariant weight-at-length therefore provides most appropriate basis to estimate biomass from the population model to correspond to the time series of biomasses from the survey (which is independent of sardine condition factor).

[8] The $l + 0.25$ denotes the middle of length class l. This function is renormalized to a maximum of 1.

[9] The proportion is calculated as the area under the curve between the lower limit and upper limit of length class l. The lower and upper tails are included in the proportions calculated for the minus and plus groups, respectively.

[10] "Selectivity" is incorporated in $F_{j,y,q,a}^{By}$, as the sardine bycaught is typically independent of sardine abundance, but rather correlated with anchovy recruitment which varies from year to year.

$$F^{By}_{j,y,q=1,a=1}=\frac{\sum_{m=11}^{12}\sum_{l\geq lcut_{y-1,m}}C^{RLF,fleet=3}_{j,y-1,m,l}+\sum_{l\geq lcut_{y,m}}C^{RLF,fleet=3}_{j,y,1,l}}{\sum_p N^S_{j,p,y,q=4,a=1}}$$

$$F^{By}_{j,y,q=2,a=0}=\frac{\sum_{m=2}^{4}\sum_{l<lcut_{y,m}}C^{RLF,fleet=3}_{j,y,m,l}}{\sum_p N^S_{j,p,y,q=2,a=0}} \qquad F^{By}_{j,y,q=2,a=1}=\frac{\sum_{m=2}^{4}\sum_{l\geq lcut_{y,m}}C^{RLF,fleet=3}_{j,y,m,l}}{\sum_p N^S_{j,p,y,q=2,a=1}}$$

$$F^{By}_{j,y,q=3,a=0}=\frac{\sum_{m=5}^{7}\sum_{l<lcut_{y,m}}C^{RLF,fleet=3}_{j,y,m,l}}{\sum_p N^S_{j,p,y,q=3,a=0}} \qquad F^{By}_{j,y,q=3,a=1}=\frac{\sum_{m=5}^{7}\sum_{l\geq lcut_{y,m}}C^{RLF,fleet=3}_{j,y,m,l}}{\sum_p N^S_{j,p,y,q=3,a=1}}$$

$$F^{By}_{j,y,q=4,a=0}=\frac{\sum_{m=8}^{10}\sum_{l<lcut_{y,m}}C^{RLF,fleet=3}_{j,y,m,l}}{\sum_p N^S_{j,p,y,q=4,a=0}} \qquad F^{By}_{j,y,q=4,a=1}=\frac{\sum_{m=8}^{10}\sum_{l\geq lcut_{y,m}}C^{RLF,fleet=3}_{j,y,m,l}}{\sum_p N^S_{j,p,y,q=4,a=1}} \qquad \text{(A20)}$$

A penalty is imposed within the model to ensure that $F^{By}_{j,y,q,a}<0.95$.

Fished proportion of the available biomass from the directed sardine catch and sardine bycatch with round herring fishery

$$F_{j,y,q=1}=\frac{\sum_{fleet=1}^{2}\sum_{m=11}^{12}\sum_{l\geq 6cm}C^{RLF,fleet}_{j,y-1,m,l}+\sum_{fleet=1}^{2}\sum_{l\geq 6cm}C^{RLF,fleet}_{j,y,1,l}}{\sum_p\sum_{a=0}^{5+}\left(N^S_{j,p,y,1,a}-C^{bycatch}_{j,y,1,a}\right)S_{j,y,1,a}}$$

$$F_{j,y,q=2}=\frac{\sum_{fleet=1}^{2}\sum_{m=2}^{4}\sum_{l\geq 6cm}C^{RLF,fleet}_{j,y,m,l}}{\sum_p\sum_{a=0}^{5+}\left(N^S_{j,p,y,2,a}-C^{bycatch}_{j,y,2,a}\right)S_{j,y,2,a}}$$

$$F_{j,y,q=3}=\frac{\sum_{fleet=1}^{2}\sum_{m=5}^{7}\sum_{l\geq 6cm}C^{RLF,fleet}_{j,y,m,l}}{\sum_p\sum_{a=0}^{5+}\left(N^S_{j,p,y,3,a}-C^{bycatch}_{j,y,3,a}\right)S_{j,y,3,a}}$$

$$F_{j,y,q=4}=\frac{\sum_{fleet=1}^{2}\sum_{m=8}^{10}\sum_{l\geq 6cm}C^{RLF,fleet}_{j,y,m,l}}{\sum_p\sum_{a=0}^{5+}\left(N^S_{j,p,y,4,a}-C^{bycatch}_{j,y,4,a}\right)S_{j,y,4,a}} \qquad \text{(A21)}$$

A penalty is imposed within the model to ensure that $S_{j,y,a,l}F_{j,y,q}<0.95$. Fish <6cm were seldom[11] caught and were thus not used in fitting this model. Commercial selectivity-at-length is fixed to zero for length classes <6cm (equation A12).

Number of recruits associated with the recruit survey

$$N^S_{j,y,r}=k^S_{j,r}\left(\left(N^S_{j,NI,y,2,0}-C^S_{j,NI,y,2,0}\right)e^{-(1/8+0.5t^S_y/12)M^S_{y,0}}-\tilde{C}^S_{j,y,0bs}\right)e^{-0.5t^S_y\times M^S_{y,0}/12} \quad 1985\leq y\leq y_n \qquad \text{(A22)}$$

Multiplicative survey bias

$$k^S_{j,N}=k^S_{ac} \qquad \text{(A23)}$$

$$k^S_{j=W,r}=k^S_{cov}\times k^S_{ac} \qquad \text{(A24)}$$

$k^S_{j=S,r}=k^S_{covS}\times k^S_{cov}\times k^S_{ac}$ (for the two mixing-component hypothesis only) (A25)

Survey trawl selectivity

$$S^{survey}_{j,l}=\begin{cases}0 & l=2.5^{-}cm\\ \left[1+exp\{-\left(l+0.25-S_{50,j}\right)/\delta_j\}\right]^{-1} & 3cm\leq l\leq 24^{+}cm\end{cases} \qquad y_1\leq y\leq y_n \text{(A26)}$$

[11] Less than 6% of the quarters west of Cape Agulhas, less than 2% of the quarters south-east of Cape Agulhas and less than 4% of the quarters for the whole coast.

Proportion-at-length associated with the November survey

$$p^{s}_{j,y,l} = \begin{cases} \frac{\sum_p \sum_{l \le 6cm} N^S_{j,p,y,l} S^{survey}_{j,l}}{\sum_p \sum_{l=2.5^-}^{24^+} N^S_{j,p,y,l} S^{survey}_{j,l}} & l = 6^- cm \\ \frac{\sum_p N^S_{j,p,y,l} S^{survey}_{j,l}}{\sum_p \sum_{l=2.5^-}^{24^+} N^S_{j,p,y,l} S^{survey}_{j,l}} & 6.5cm \le l \le 20.5cm \\ \frac{\sum_p \sum_{l=21}^{23.5} N^S_{j,p,y,l} S^{survey}_{j,l}}{\sum_p \sum_{l=2.5^-}^{24^+} N^S_{j,p,y,l} S^{survey}_{j,l}} & l = 21 - 23.5cm \\ \frac{\sum_p N^S_{j,p,y,l} S^{survey}_{j,24^+}}{\sum_p \sum_{l=2.5^-}^{24^+} N^S_{j,p,y,l} S^{survey}_{j,l}} & l = 24^+ cm \end{cases} \quad {}^{12} \quad y_1 \le y \le y_n \tag{A27}$$

Proportion-at-length of fish infected with the parasite in November

$$P^S_{j,y,l} = \frac{N^S_{j,I,y,l}}{\sum_p N^S_{j,p,y,l}} \quad y_1 \le y \le y_n, 10\ cm \le l \le 23\ cm \tag{A28}$$

Catch-at-length from the directed and round herring bycatch fisheries

$$C^{dir}_{j,p,y,q,l} = \sum_{a=0}^{5^+} \left(N^S_{j,p,y,q,a} - C^{bycatch}_{j,p,y,q,a} \right) A^{com}_{j,q,a,l} S_{j,y,q,l} F_{j,y,q} \quad {}^{13}$$

$$p = I, NI, y_1 \le y \le y_n, 1 \le q \le 4, 2.5^- cm \le l \le 24^+ cm \tag{A29}$$

Proportion-at-length associated with the directed catch and round herring bycatch

$$p^{coml,S}_{j,y,q,l} = \begin{cases} \frac{\sum_p C^{dir}_{j,p,y,q,l}}{\sum_p \sum_{l=6}^{24^+} C^{dir}_{j,p,y,q,l}} & 6cm \le l \le 22.5cm \\ \frac{\sum_p \sum_{l=23}^{24^+} C^{dir}_{j,p,y,q,l}}{\sum_p \sum_{l=6}^{24^+} C^{dir}_{j,p,y,q,l}} & l = 23^+ cm \end{cases} \quad {}^{14} \quad y_1 \le y \le y_n, 1 \le q \le 4 \tag{A30}$$

<u>Fitting the Model to Observed Data (Likelihood)</u>

$$-lnL = -lnL^{Nov} - lnL^{rec} - lnL^{sur\,propl} - lnL^{com\,propl} - lnL^{prev} \tag{A31}$$

where

$$-lnL^{Nov} = 0.5 \sum_j \sum_{y=y_1}^{y_n} \left\{ \frac{5^5 \left(\frac{\left| ln\left(\hat{B}^S_{j,y}\right) - ln\left(B^S_{j,y}\right) \right|}{\sqrt{\left(\sigma^S_{j,y,Nov}\right)^2 + \left(\phi^S_{ac}\right)^2 + \left(\lambda^S_{j,N}\right)^2}} \right)^5}{5^5 + \left(\frac{\left| ln\left(\hat{B}^S_{j,y}\right) - ln\left(B^S_{j,y}\right) \right|}{\sqrt{\left(\sigma^S_{j,y,Nov}\right)^2 + \left(\phi^S_{ac}\right)^2 + \left(\lambda^S_{j,N}\right)^2}} \right)^5} \right\}^{2/5} + ln\left[2\pi \left(\left(\sigma^S_{j,y,Nov}\right)^2 + (\phi^S_{ac})^2 + \left(\lambda^S_{j,N}\right)^2 \right) \right] \tag{A32}$$

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[12] The inclusion of model predicted proportion-at-length 24⁺cm is deliberate to take into account the zero samples of 24⁺cm sardine in the survey.

[13] Note the model predicted commercial catch of lengths <6cm is zero, from a zero commercial selectivity in equation A.13. This is consistent with the range of length classes in the observed commercial proportions-at-lengths.

[14] Note the model predicted commercial catch of lengths <6cm is zero, from a zero commercial selectivity in equation A.13. This is consistent with the range of length classes in the observed commercial proportions-at-lengths.

$$-lnL^{rec} = 0.5\sum_j \sum_{y=y_2}^{y_n} \left\{ \frac{5^5\left(\frac{\left|ln\left(\hat{N}^S_{j,y,r}\right)-ln\left(N^S_{j,y,r}\right)\right|}{\sqrt{\left(\sigma^S_{j,y,rec}\right)^2+\left(\phi^S_{ac}\right)^2+\left(\lambda^S_{j,r}\right)^2}}\right)^5}{5^5+\left(\frac{\left|ln\left(\hat{N}^S_{j,y,r}\right)-ln\left(N^S_{j,y,r}\right)\right|}{\sqrt{\left(\sigma^S_{j,y,rec}\right)^2+\left(\phi^S_{ac}\right)^2+\left(\lambda^S_{j,r}\right)^2}}\right)^5} \right\}^{2/5} + ln\left[2\pi\left(\left(\sigma^S_{j,y,rec}\right)^2+\left(\phi^S_{ac}\right)^2+\left(\lambda^S_{j,r}\right)^2\right)\right] \qquad \text{(A33)}$$

$$-lnL^{sur\,propl} = w^{sur}_{propl}\sum_j \sum_{y=y_1}^{y_n} \left\{ \sum_{l=6^-}^{21^+} \left\{ \frac{\left(\sqrt{\hat{p}^S_{j,y,l}}-\sqrt{p^S_{j,y,l}}\right)^2}{2\left(\sigma^S_{j,sur}\right)^2} + ln\left(\sigma^S_{j,sur}\right) \right\} + \frac{\left(0-\sqrt{p^S_{j,y,24^+}}\right)^2}{2\left(\sigma^S_{j,sur}\right)^2} + ln\left(\sigma^S_{j,sur}\right) \right\} \text{[15]} \qquad \text{(A34)}$$

$$-lnL^{com\,propl} = w^{com}_{propl}\sum_j \sum_{y=y_1}^{y_n} \sum_{q=1}^{4} \sum_{l=6}^{23^+} \left\{ \frac{\left(\sqrt{\hat{p}^{S,coml}_{j,y,q,l}}-\sqrt{p^{S,coml}_{j,y,q,l}}\right)^2}{2\left(\sigma^S_{j,com}\right)^2} + ln\left(\sigma^S_{j,com}\right) \right\} \qquad \text{(A35)}$$

$$-lnL^{prev} = \sum_j \sum_{y=2010}^{2018} \sum_{l=10cm}^{23cm} -n^{prev}_{j,y,l}\, ln\left(P^S_{j,y,l}\right) - \left(N^{prev}_{j,y,l} - n^{prev}_{j,y,l}\right) ln\left(1-P^S_{j,y,l}\right) \qquad \text{(A36)}$$

A "robustified likelihood" is used for the contributions from the hydro-acoustic surveys to ensure no undue influence from any extreme (outlying) values for residuals. The functional form chosen to robustify makes negligible difference for standardised residuals of magnitude three or less, but essentially treats large standardised residuals as if they do not exceed five in magnitude.

[15] The 21^+ group in this equation consists of the length classes 21cm, 21.5cm, 22cm, 22.5cm, 23cm and 23.5cm.

Table A1. Assessment model parameters and variables with associated fixed values or prior distributions and, for derived variables, associated equation numbers. As the majority of prior distributions are uninformative, notes are provided only for informative priors and/or bounds.

	Parameter / Variable	Description	Units / Scale	Fixed Value / Prior Distribution	Equation	Notes
Annual numbers and biomass	$N^S_{j,p,y,a}$	Model predicted numbers-at-age a at the beginning of November in year y of component j that are uninfected ($p = NI$) or infected ($p = I$) with the endoparasite	Billions	$ln(N^S_{j,NI,y,0})/10 \sim U(-10,3.$ $N^S_{j,I,y,0} = 0$	A1 - A3	
	$N^S_{j,p,1983,a}$	Initial numbers-at-age a in component j	Billions	$N^S_{j,NI,1983,a=1} \sim U(0,50)$ $N^S_{j,NI,1983,a} = 0,\ 2 \leq a \leq 5^+$ $N^S_{j,I,1983,a} = 0,\ 0 \leq a \leq 5^+$		
	$N^S_{j,p,y,q,a}$	Model predicted numbers-at-age a mid-way through quarter q of year y of component j that are uninfected ($p = NI$) or infected ($p = I$) with the endoparasite	Billions		A4	
	I_y	Proportion of uninfected west component sardine that are infected with the endoparasite in year y (two mixing-component hypothesis only)		$= 0,\ y_1 \leq y \leq 2007$ $\sim U(0,1),\ 2008 \leq y \leq y_n$		
	$move_{y,a}$	Proportion of west component sardine of age a which move to the south component at the beginning of November of year y (two mixing-component hypothesis only)	-	$move_{y,1} \sim Beta(1.05,1.05)$ $move_{y,2+} = \phi move_{y,1}$ $\phi \sim U(0,1)$		
	$SSB^S_{j,y}$	Model predicted spawning biomass of component j at the beginning of November in year y	Thousand tons		A11	
	$SSB^{eff,S}_{j,y}$	Model predicted effective spawning biomass of component j at the beginning of November in year y	Thousand tons		A12	
	$B^S_{j,y}$	Model predicted total biomass of component j at the beginning of November in year y, associated with the November survey	Thousand tons		A13	
	ξ_j	Proportion of j-component spawner biomass that contributes to the effective spawning biomass on the same coast		0.08		Alternative values considered in robustness tests
	$w^S_{j,l}$	Mean mass of sardine of component j in length class l	Grams	$5.6876 \times 10^{-6} \times l^{3.140026}$		OLSPS (2020)

Table A1 (Continued).

	Parameter / Variable	Description	Units / Scale	Fixed Value / Prior Distribution	Equation	Notes
Annual numbers and biomass	$f^S_{j,y,l}$	Proportion of component j sardine that are mature in length class l in year y	-	$\left[1+e^{-(l-17.2)/1.17}\right]^{-1}$ $1984 \leq y \leq 1987$ $\left[1+e^{-(l-18.6)/1.26}\right]^{-1}$ $1988 \leq y \leq 1995$ $\left[1+e^{-(l-19.4)/1.40}\right]^{-1}$ $1996 \leq y \leq 2003$ $\left[1+e^{-(l-17.4)/0.95}\right]^{-1}$ $2004 \leq y \leq 2018$		Refit from data used by van der Lingen *et al*. (2006) using midpoints of length classes. Assuming maturity post-2003 reflects that of 1965-1975 as maturity is hypothesized to be density dependent (van der Lingen *et al*. 2006) and both these periods correspond to low biomass following a peak in abundance
	$N^S_{j,y,r}$	Model predicted number of juveniles of component j at the time of the recruit survey in year y	Billions		A23	
Natural mortality	$M^S_{y,a}$	Rate of natural mortality of age a in year y	Year^{-1}	$M^S_{y,0} = 1.0$ $M^S_{y,1+} = 1.0$	A9 and A10	Selected based on maximized joint posterior, and subject to a compelling reason to modify from previous assessment
	$\bar{M}^S_{ju}$	Median juvenile rate of natural mortality	Year^{-1}	1.0		
	$\bar{M}^S_{ad}$	Median rate of natural mortality for 1+ sardine	Year^{-1}	0.8		
	ε^{ju}_y	Annual residuals about juvenile natural mortality rate	-		A9	
	ε^{ad}_y	Annual residuals about natural mortality rate for 1+ sardine	-		A10	
	η^{ju}_y	Normally distributed error in calculating ε^{ju}_y	-	$N\left(0,\sigma^2_j\right)$		
	η^{ad}_y	Normally distributed error in calculating ε^{ad}_y	-	$N(0,\sigma^2_{ad})$		
	σ_j	Standard deviation in the annual residuals about juvenile natural mortality	-	0		See robustness tests
	σ_{ad}	Standard deviation in the annual residuals about natural mortality for ages 1+	-	0		See robustness tests
	ρ	Annual autocorrelation coefficient	-	0		See robustness tests

Table A1 (Continued).

	Parameter / Variable	Description	Units / Scale	Fixed Value / Prior Distribution	Equation	Notes
Proportions-at-length and growth curve	$N^{S}_{j,p,y,l}$	Model predicted numbers-at-length l at the beginning of November in year y of component j that are uninfected ($p = NI$) or infected ($p = I$) with the endoparasite	Billions		A5	
	$p^{S}_{j,y,l}$	Model predicted proportion-at-length l of component j associated with the November survey in year y	-		A27	
	$A^{sur}_{j,y,a,l}$	Proportion of age a of component j sardine that falls in the length group l in November of year y	-		A7	
	κ_j	Somatic growth rate parameter for component j	Year^{-1}	$U(0,3)$		
	$L_{j,\infty}$	Maximum length (in expectation) of component j	Cm	$L_{j,\infty} = \frac{L_{j,1}e^{-2\kappa_j}-L_{j,3}}{e^{-2\kappa_j}-1}$ where $L_{j,a=1} \sim U(5,25)$ $L_{j,a=3} - L_{j,a=1} \sim U(5,25)$		
	$L^{small}_{j,\infty,y}$	Maximum length (in expectation) of component $j = 1$ for the growth curve below $a \acute{=} 0.5$ years in year y	Cm	$= \dfrac{L_{j,\infty}\left(1 - e^{-\kappa_j(\acute{a}-t_{0,j,y})}\right)}{\left(1 - e^{-1.5\kappa_j\left(\acute{a}-t^{small}_{0,j,y}\right)}\right)}$		
	$t_{0,j,y}$	Age at which the length (in expectation) is zero for component j in year y	Year		A8	
	$t^{small}_{0,j,y}$	Age at which the length (in expectation) is zero for component $j = 1$ in year y for the growth curve below $a = 0.5$ years	Year	$= \dfrac{1}{1.5\kappa_j} ln\left(\dfrac{e^{1.5\kappa_j\acute{a}-\kappa_j(\acute{a}-t_{0,j,y})}}{1.5 + (1-1.5)e^{-\kappa_j(\acute{a}-t_{0,j,y})}}\right)$		
	$t_{0,j}$	Average age at which the length (in expectation) is zero	Year	$\dfrac{1}{\kappa_j} ln\left\{\dfrac{e^{\kappa_j}\left(L_{j,1} - L_{j,3}\right)}{L_{j,1}e^{-2\kappa_j} - L_{j,3}}\right\}$		
	ε^{t}_{y}	Annual autocorrelated residuals about the age at which the length is zero			A8	
	η^{t}_{y}	Annual uncorrelated residuals about the age at which the length is zero		$N(0, 0.2^2)$		
	ρ^{t}	Autocorrelation coefficient in these residuals		$U(-1,1)$		
	ϑ_a	Standard deviation of the distribution about the mean length for age a	-	$U(0,3)$, $a = 0,1,2^{+}$		Upper bound precludes unrealistically large lengths for young fish
	$p^{com,S}_{j,y,q,l}$	Model predicted proportion-at-length l of component j in the directed catch and round herring bycatch during quarter q of year y	-		A30	
	$A^{com}_{j,y,q,a,l}$	Proportion of age a of component j sardine that falls in the length group l mid-way through quarter q of year y	-		A16	
	$P^{S}_{j,y,l}$	Model predicted proportion-at-length l of component j that are infected with the endoparasite, at the time of the November survey in year y			A28	

Table A1 (Continued).

	Parameter / Variable	Description	Units / Scale	Fixed Value / Prior Distribution	Equation	Notes
Selectivity	$S_{j,l}^{survey}$	Survey selectivity-at-length l in the November survey for component j	-		A26	Some smaller fish escape through the trawl net
	$S_{50,j}$	Length at which survey selectivity is 50% for component j	Cm	$U(2.5,20)$		
	δ_j	Inverse of slope of survey selectivity-at-length ogive when selectivity is 50% for component j	-	$U(0.05,50)$		
	$S_{j,y,q,l}$	Commercial selectivity-at-length l during quarter q of year y of component j	-		A14	
	$S_{j,y,q,a}$	Commercial selectivity-at-age a during quarter q of year y of component j	-		A15	
	$\chi_{j,y,q}$	Height of the Gaussian component for component j relative to the height of the logistic component in quarter q of year y	-	$U(0,1)$ for $j=1$ = 0 for $j=2$		No bycatch modelled for south component
	$\bar{l}_{1,y}$	Mean of the Gaussian distribution for in year y	mm	$N(100,10^2)$		
	$\bar{l}_{2,j,y,q}$	Length at 50% selectivity in the logistic component for component j in quarter q of year y	mm	$\bar{l}_{2,j,y,1}-\bar{l}_{1,2000}\sim U(0,150)$ $\bar{l}_{2,j,y,2}-\bar{l}_{1,2000}\sim U(0,150)$ $\bar{l}_{2,j,y,3}=\bar{l}_{2,j,y,2}$ $\bar{l}_{2,j,y-1,4}=\bar{l}_{2,j,y12}$		Estimated for two time periods per component: 1984-1993, 1994-2018 (west) and 1984-1997, 1998-2018 (south)
	$(\sigma_1^{sel})^2$	Variance parameter of the Gaussian distribution	mm	$U(20,150)$		
	$(\sigma_2^{sel})^2$	Variance parameter of the logistic distribution	mm	$U(0,100)$		
Multiplicative bias	$k_{j,N}^S$	Multiplicative bias associated with the November survey of component j	-		A23	
	$k_{j,r}^S$	Multiplicative bias associated with the recruit survey of component j	-		A24 – A25	
	k_{ac}^S	Multiplicative bias associated with the hydro-acoustic survey	-	$ln(k_{ac}^S)\sim N(-0.311,0.094^2)$		Appendix B of de Moor and Butterworth (2016)
	k_{cov}^S	Multiplicative bias associated with the coverage of the recruits during the recruit survey in comparison to the coverage of the biomass during the November survey	-	Uniform prior on logit transpose of k_{cov}^S, such that $0.3\le k_{cov}^S\le 1$		Lower bound selected in discussions with scientists on these surveys and their field experience
	k_{covS}^S	Multiplicative bias associated with the coverage of the south component recruits in comparison to the west component recruits during the recruit survey		$U(0,1)$		

Table A1 (Continued).

	Parameter / Variable	Description	Units / Scale	Fixed Value / Prior Distribution	Equation	Notes
Catch	$C^{S}_{j,p,y,q,a}$	Model predicted number of age a fish of component j caught during quarter q of year y that are uninfected ($p = NI$) or infected ($p = I$) with the endoparasite	Billions		A19	
	$lcut_{y,m}$	Cut off length for recruits in month m of year y	Cm	de Moor *et al*. 2019		Differ by month and year as informed by the recruit surveys
	$C^{bycatch}_{j,p,y,q,a}$	Number of age a fish of component j bycaught in the anchovy-directed fishery in quarter q of year y that are uninfected ($p = NI$) or infected ($p = I$) with the endoparasite	Billions		A17	
	$C^{dir}_{j,p,y,q,a}$	Number of age a fish of component j caught in the sardine-directed and round herring bycatch fisheries in quarter q of year y that are uninfected ($p = NI$) or infected ($p = I$) with the endoparasite	Billions		A18	
	$C^{dir}_{j,p,y,q,l}$	Number of length l fish of component j caught in the sardine-directed and round herring bycatch fisheries in quarter q of year y	Billions		A29	
	$F^{By}_{j,y,q,a}$	Fished proportion in quarter q of year y for age class a of component j, of bycatch in the anchovy-directed fishery	-		A20	
	$F_{j,y,q}$	Fished proportion in quarter q of year y for a fully selected age class a of component j, by the directed and round herring bycatch fisheries	-		A21	
Likelihood	$-lnL^{Nov}$	Contribution to the negative log likelihood from the model fit to the November survey biomass data	-		A32	
	$-lnL^{rec}$	Contribution to the negative log likelihood from the model fit to the recruit survey data	-		A33	
	$-lnL^{surpropl}$	Contribution to the negative log likelihood from the model fit to the November survey proportion-at-length data	-		A34	
	$-lnL^{compropl}$	Contribution to the negative log likelihood from the model fit to the quarterly commercial proportion-at-length data	-		A35	
	$-lnL^{surprev}$	Contribution to the negative log likelihood from the model fit to the November parasite prevalence-at-length data	-		A36	
	ϕ^{S}_{ac}	CV associated with factors which cause bias in the acoustic survey estimates and which vary inter-annually rather than remain fixed over time	-	=0.227		Appendix B of de Moor and Butterworth (2016)
	$\left(\lambda^{S}_{j,N/r}\right)^2$	Additional variance (over and above $\left(\sigma^{S}_{j,y,Nov/rec}\right)^2$ and $(\phi^{S}_{ac})^2$) associated with the November/recruit surveys of component j	-	$U(0,10)$		

Table A1 (Continued).

Parameter / Variable	Description	Units / Scale	Fixed Value / Prior Distribution	Equation	Notes
w_{propl}^{sur}	Weighting applied to the remaining survey proportion-at-length data	-	$= 0.5 \times 0.167$		To allow for autocorrelation[16]
$\sigma_{j,sur}^{S}$	Standard deviation associated with the survey proportion-at-length data of component *j*	-		$\sqrt{\frac{\sum_{y=y_1}^{y_n}\sum_{l=6^-}^{21^+}\left(\sqrt{\hat{p}_{j,y,l}^{S}}-\sqrt{p_{j,y,l}^{S}}\right)^2}{\sum_{y=y_1}^{y_n}\sum_{l=6^-}^{21^+}1}}$[17]	Closed form solution
w_{propl}^{com}	Weighting applied to the commercial proportion-at-length data		$= 0.5 \times 0.04$		To allow for autocorrelation[18]
$\sigma_{j,com}^{S}$	Standard deviation associated with the commercial proportion-at-length data of stock *j*	-	$\sqrt{\frac{\sum_{y=y_1}^{y_n}\sum_{q=1}^{4}\sum_{l=6}^{23^+}\left(\sqrt{\hat{p}_{j=1,y,q,l}^{comlS}}-\sqrt{\right.}}{\sum_{y=y_1}^{y_n}\sum_{q=1}^{4}\sum_{l=6}^{23^+}1}}$ $\sqrt{\frac{\sum_{y=y_1}^{y_n}\sum_{q=1}^{4}\sum_{l=13}^{23^+}\left(\sqrt{\hat{p}_{j=2,y,q,l}^{comlS}}-\sqrt{\right.}}{\sum_{y=y_1}^{y_n}\sum_{q=1}^{4}\sum_{l=13}^{23^+}1}}$	Closed form solution[19]	$\sigma_{j,com}^{S}$

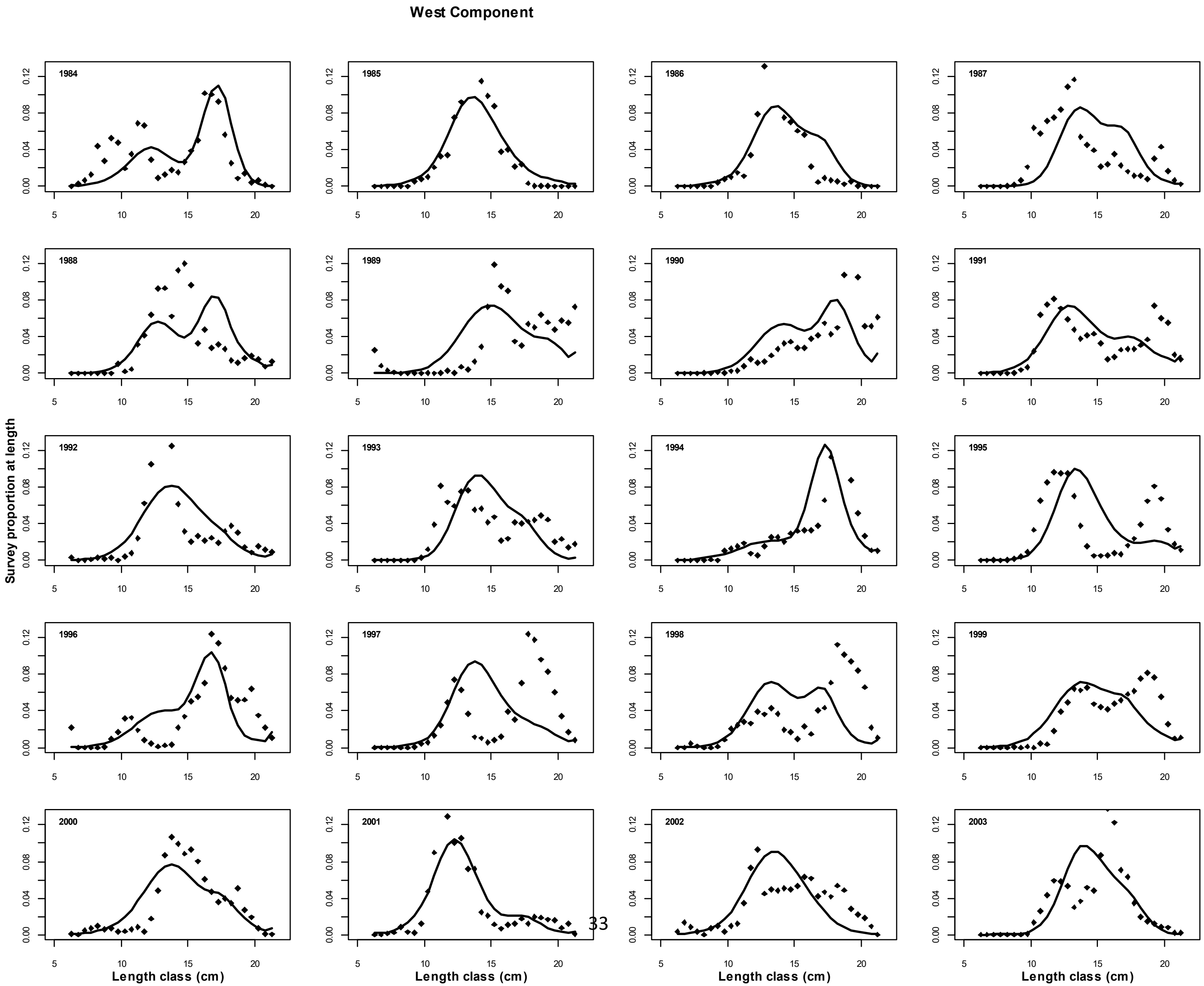
[16] Based upon data being available ~6 times more frequently than annual age data which contain maximum information content on this.
[17] The 21⁺ group in this equation consists of the length classes 21cm, 21.5cm, 22cm, 22.5cm, 23cm and 23.5cm.
[18] Based upon data being available ~4x6 times more frequently than annual age data which contain maximum information content on this.
[19] A shorter range of lengths is used for the south component given the near absence of data outside this range, resulting in small/zero residuals, which would negatively bias this estimate.

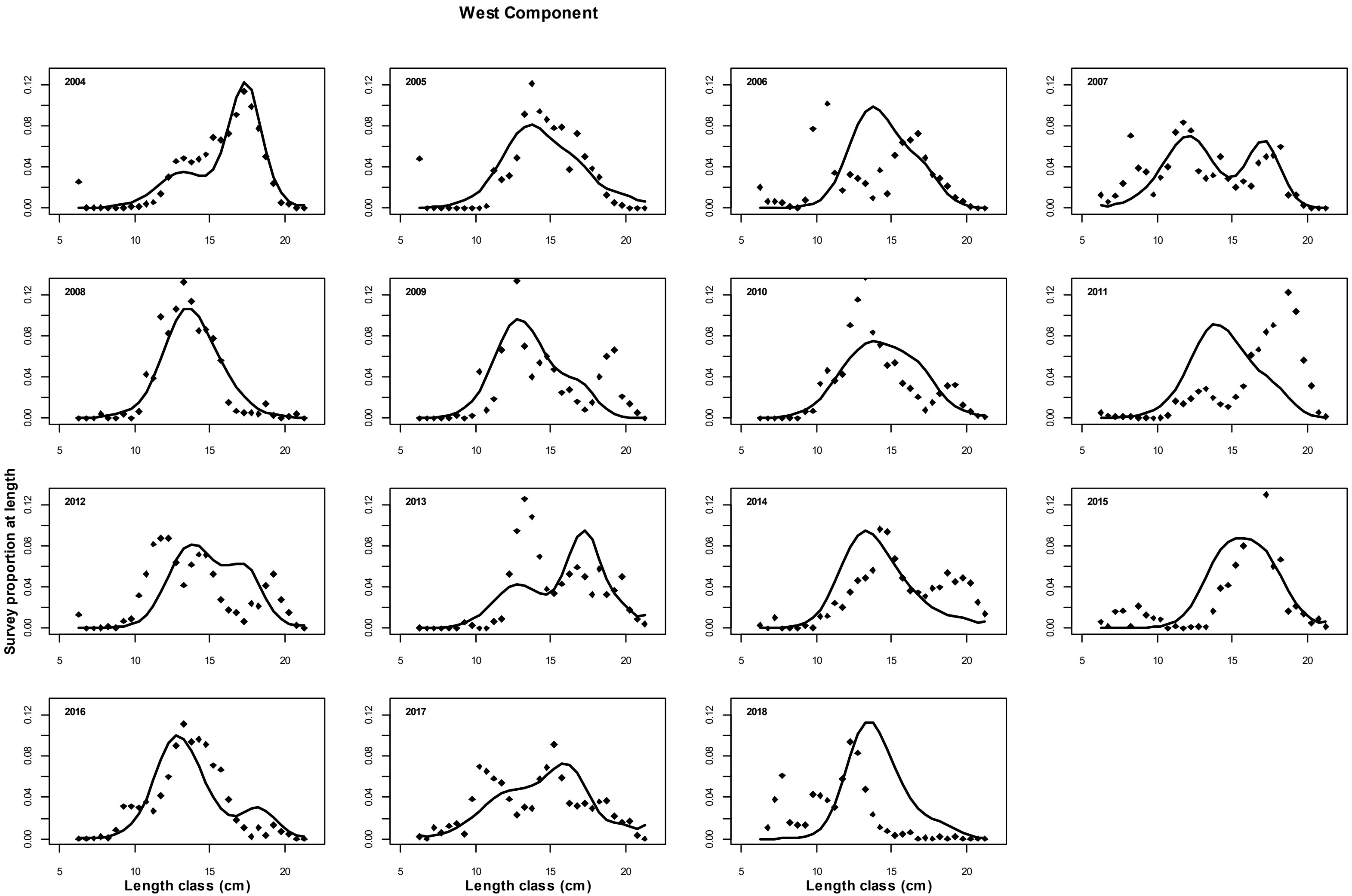
Table A2. Assessment model data, detailed in de Moor *et al*. (2019)[20].

Quantity	Description	Units / Scale	Shown in Figure
t_y^S	Time lapsed between 1 May and the start of the recruit survey in year y	Months	
$\tilde{C}_{j,y,0bs}^S$	Number of juveniles of component j caught between 1 May and the day before the start of the recruit survey in year y	Billions	
$C_{j,y,m,l}^{RLF,fleet}$	Number of fish in length class l landed by $fleet$ in month m of year y of component$j$. $fleet = 1$ denotes the sardine directed fishery, $fleet = 2$ denotes the sardine bycatch with round herring (1984-2011) or ≥14cm sardine bycatch (2012-18) and $fleet = 3$ denotes the juvenile sardine bycatch with anchovy (1984-2011) or <14cm sardine bycatch (2012-18)	Billions	
$\hat{B}_{j,y}^S$	Acoustic survey estimate of biomass of component j from the November survey in year y	Thousand tons	Fig. 1
$\sigma_{j,y,Nov}^S$	Survey sampling CV associated with $\hat{B}_{j,y}^S$ that reflects survey inter-transect variance	-	Fig. 1
$\hat{N}_{j,y,r}^S$	Acoustic survey estimate of recruitment of component j from the recruit survey in year y	Billions	Fig. 2
$\sigma_{j,y,rec}^S$	Survey sampling CV associated with $\hat{N}_{j,y,r}^S$ that reflects survey inter-transect variance	-	Fig. 2
$\hat{p}_{j,y,l}^S$	Observed proportion (by number) of component j in length group l in the November survey of year y	-	Fig. 6
$\hat{p}_{j,y,q,l}^{S,com}$	Observed proportion (by number) of the directed catch and round herring bycatch of fish of component j and length group l during quarter q of year y	-	Fig. 9
$n_{j,y,l}^{prev}$	Number of sardine of component j in length class l sampled from the November survey in year y that were tested and found to be infected with the endoparasite	Numbers	Fig. 13
$N_{j,y,l}^{prev}$	Number of sardine of component j in length class l sampled from the November survey in year y that were tested for infection with the endoparasite	Numbers	Fig. 13

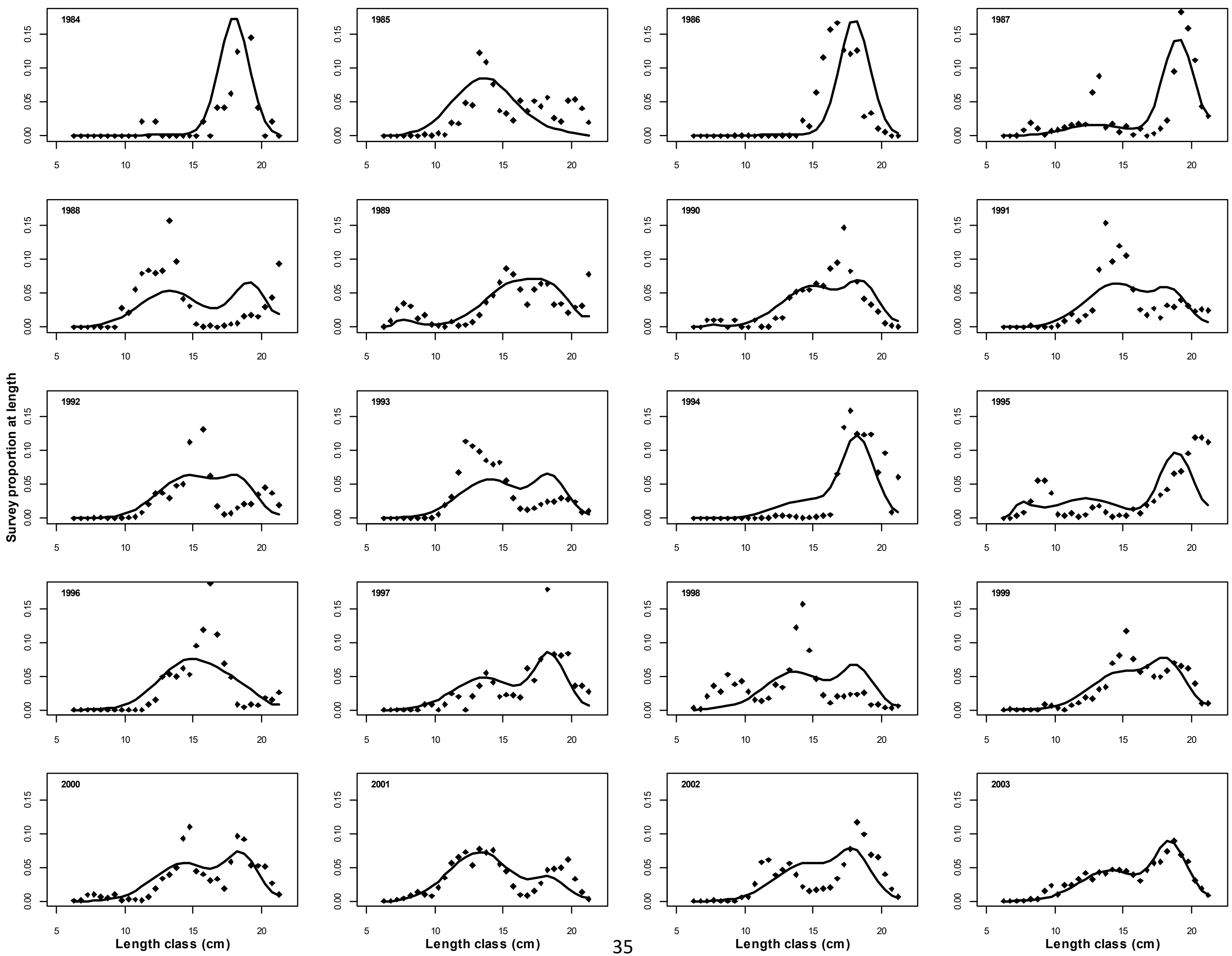
[20] Note that the expected mass by length class and month, used to calculate $C_{j,y,m,l}^{RLF,fleet}$ and $\tilde{C}_{j,y,0bs}^S$, is given by $EM_{y,l,m} = 0.0000090193 \times l_{mid}^{3.066305} \times N_{y,l,m}$ for the west component and $EM_{y,l,m} = 0.00023041 \times l_{mid}^{2.463739} \times N_{y,l,m}$ for the south component.

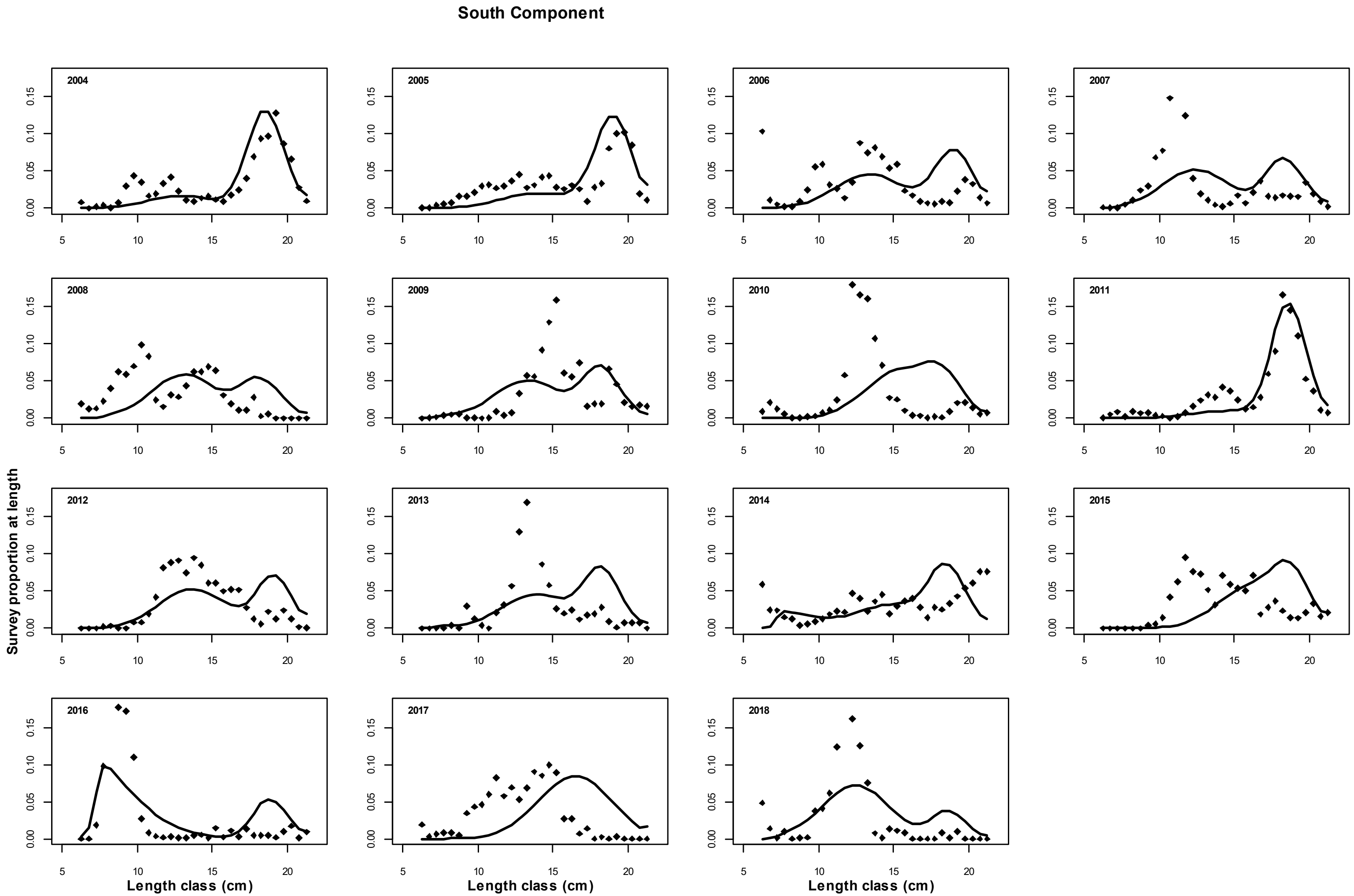
Appendix B: Detailed comparison between model predicted and observed commercial length frequencies




West Component
Survey proportion at length
Length class (cm)
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018
0.00
0.04
0.08
0.12
5
10
15
20

South Component




South Component
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018
Survey proportion at length
Length class (cm)
0.00
0.05
0.10
0.15
5
10
15
20